CALIFORNIA
ENERGY
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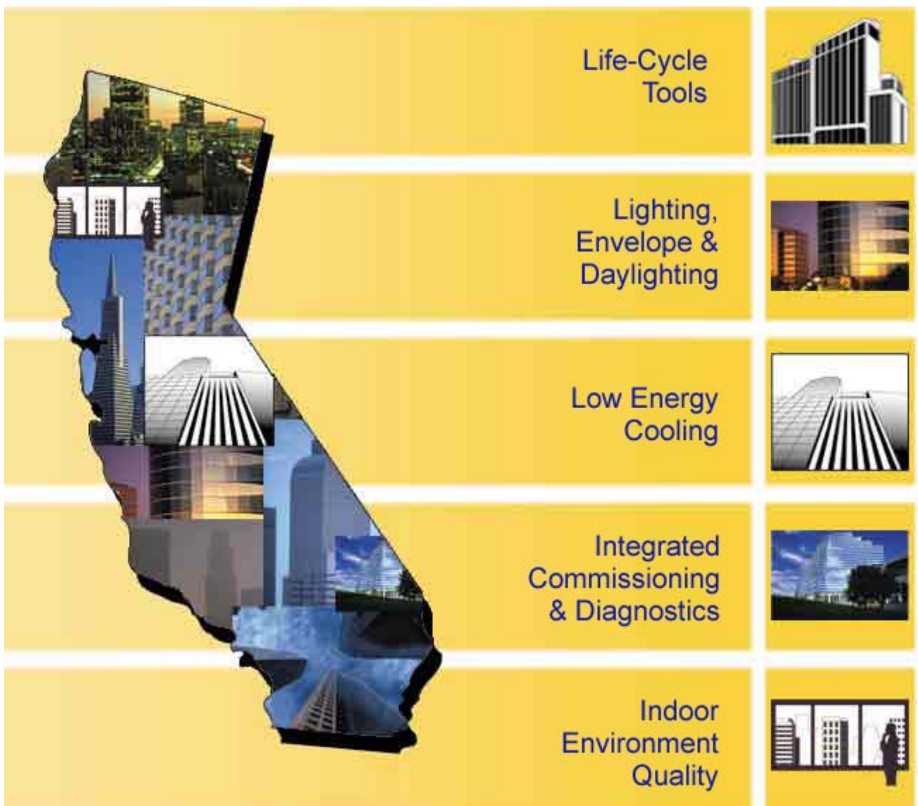
Building Performance Assessment using On-Line Simulations



TECHNICAL REPORT

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CALIFORNIA ENERGY COMMISSION

Prepared By:
Buildings Technologies Department
Lawrence Berkeley National Laboratory

Steve Selkowitz
B90R3110
1 Cyclotron Road
E. O. Lawrence Berkeley National Laboratory
Berkeley, CA 94720

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Prepared For:
Martha Brook,
Contract Manager

Nancy Jenkins,
PIER Buildings Program Manager

Terry Surles,
PIER Program Director

Robert L. Therkelsen
Executive Director

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Program's final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the High Performance Commercial Building Systems (HPCBS) Program. This Commercial Building Energy Benchmarking attachment provides supplemental information to the final report (Commission publication # 500-03-097-A2). The reports, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This document is the nineteenth of 22 technical attachments to the final report, and consists of research reports:

- Use of Whole Building Simulation In On-Line Performance Assessment: Modeling and Implementation Issues (E5P2.3T1a1)
- Potential of On-line Simulation for Fault Detection and Diagnosis in Large Commercial Buildings with Built-up HVAC Systems (E5P2.3T2b)
- Manual of Procedures for Calibrating Simulations of Building Systems (E5P2.3T2b)

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-012). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

For the final report, other attachments or reports produced within this contract, or to obtain more information on the PIER Program, please visit http://www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The reports and attachments are also available at the HPCBS website: http://buildings.lbl.gov/hpcbs/.

Abstracts

Use Of Whole Building Simulation In On-Line Performance Assessment: Modeling And Implementation Issues

The application of model-based performance assessment at the whole building level is explored. The information requirements for a simulation to predict the actual performance of a particular real building, as opposed to estimating the impact of design options, are addressed with particular attention to common sources of input error and important deficiencies in most simulation models. The role of calibrated simulations is discussed. The communication requirements for passive monitoring and active testing are identified and the possibilities for using control system communications protocols to link on-line simulation and energy management and control systems are discussed. The potential of simulation programs to act as "plug-and-play" components on building control networks is discussed.

Potential of On-line Simulation for Fault Detection and Diagnosis in Large Commercial Buildings with Built-up HVAC Systems

This report presents the results of a study of the potential for using simulation programs for on-line fault detection, problem diagnosis, and operational schedule optimization for large commercial buildings with built-up HVAC systems. This study reviewed over a dozen simulation programs and determined that AirModel and EnergyPlus were most suitable for initial use in the on-line simulation applications that are the focus of this study.

Relevant characteristics of these programs include the following:

EnergyPlus is a detailed system performance simulation program. It can perform detailed load and system performance simulation.

AirModel is a simplified system performance simulation program. It can perform simplified load and detailed system performance simulation. It differs from EnergyPlus in the level of detail of the building load modeling, including the number of zones. It allows the modeling of actual system performance, such as leaking dampers.

Both EnergyPlus and AirModel have the capability to: (a) identify in-efficient operation at the whole building level, (b) identify major time invariant mechanical systems, (c) develop improved and optimized operational and control schedules and set points, and (d) project potential energy savings.

Both EnergyPlus and Airmodel can be used for on-line simulation and fault detection after revising the input structures of the program.

Airmodel can be embedded in existing energy management and control systems. On-line simulation can be conducted without major revision to the program.

Manual of procedures for calibrating simulations of building systems

The calibration of a cooling and heating energy consumption simulation typically consists of closely matching the simulation results to measured consumption from utility bills or actual data.

However, the calibration processes used to achieve agreement have generally been quite time-consuming. There would be tremendous value in having a procedure that can quickly and reliably calibrate simulations of large commercial buildings with built-up HVAC systems. Then, it would be practical to use a calibrated simulation for energy audits (to determine the potential savings from proposed retrofit measures), to explore the potential savings from changing building operational strategies or to track the building's performance over time in support of fault detection activities.

This manual presents a methodology for the rapid calibration of cooling and heating energy consumption simulations for commercial buildings based on the use of "calibration signatures", which characterize the difference between measured and simulated performance. The method is described and then its use is demonstrated in two illustrative examples and two real-world case studies. This document contains characteristic calibration signatures suitable for use in calibrating energy simulations of large buildings with four different system types: single-duct variable-volume, single-duct constant-volume, dual-duct variable-volume and dual-duct constant-volume. Separate sets of calibration signatures are presented for each system type for the climates typified by Pasadena, Sacramento and Oakland, California.

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HPCBS

High Performance Commercial Building Systems

Use of whole building simulation in on-line performance assessment: Modeling and implementation issues

Element 5. Integrated Commissioning and Diagnostics
Project 2.3 - Advanced Commissioning and Monitoring Techniques
Task 2.3.1 - Develop simulation-assisted commissioning procedures

Philip Haves,
Lawrence Berkeley National Laboratory
Tim Salsbury,
Johnson Controls Inc.
David Claridge,
Texas A&M University
Mingsheng Liu,
University of Nebraska

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USE OF WHOLE BUILDING SIMULATION IN ON-LINE PERFORMANCE ASSESSMENT: MODELING AND IMPLEMENTATION ISSUES

Philip Haves
Building Technologies Department
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
1 Cyclotron Road
Berkeley, California 94720

Tim Salsbury
Johnson Controls Inc.
Mlwaukee, Wisconsin

David Claridge
Texas A&M University
College Station, Texas

Mingsheng Liu
University of Nebraska
Omaha, Nebraska

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Philip Haves, Lawrence Berkeley National Laboratory
Tim Salsbury, Johnson Controls Inc., Milwaukee, Wisconsin
David Claridge, Texas A&M University, College Station, Texas
Mingsheng Liu, University of Nebraska, Omaha, Nebraska

ABSTRACT

The application of model-based performance assessment at the whole building level is explored. The information requirements for a simulation to predict the actual performance of a particular real building, as opposed to estimating the impact of design options, are addressed with particular attention to common sources of input error and important deficiencies in most simulation models. The role of calibrated simulations is discussed. The communication requirements for passive monitoring and active testing are identified and the possibilities for using control system communications protocols to link on-line simulation and energy management and control systems are discussed. The potential of simulation programs to act as "plug-and-play" components on building control networks is discussed.

INTRODUCTION

There is an increasing realization that many buildings do not perform as intended by their designers. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures. The first step in detecting and diagnosing such problems is the evaluation of building performance. A quantitative evaluation of performance requires a baseline or reference, against which to compare the actual performance. Possible sources of such a baseline include:

1. The previous performance of comparable buildings
2. The current performance of comparable buildings
3. The previous performance of the building in question
4. The intended performance of the building in question

In the first case, a database of the actual performance of a statistically selected sample of buildings is used to compare the performance of the building in question to that of similar buildings. The comparison is usually made in terms of whole building electricity and fuel consumption. This 'benchmarking' process can provide an approximate assessment of relative performance from very modest input data, typically building type, floor area and geographical location. Benchmarking is a useful screening tool, allowing attention to be focused on those buildings that appear to be performing poorly.

In the second case, owners of campuses or chains with suitable monitoring capabilities can make comparisons between buildings on the time-scale of an hour to a week to detect the onset of malfunctions that have a significant effect at the whole building level. This quasi-real-time form of benchmarking provides a relatively simple method of detecting significant degradations in performance before the cumulative effects of that degradation become severe.

In both the first and second cases, simple regression models are typically used to correct for differences between the conditions under which the actual performance is observed and the conditions for the baseline. However, simulation models are starting to be used as interpolation tools for more sophisticated benchmarking where more information about the buildings and their energy systems is available.

In the third case, the previous performance can be represented using a 'calibrated simulation', in which the parameters of the model are adjusted to minimize the difference between the predicted and measured performance over a selected period. The model can either be a detailed first principles model, such as EnergyPlus (Crawley et al. 2000), DOE-2 (LBNL 1982) or ESP (ESRU 2000), a simplified first principles model, such as AIRMODEL (Liu and Claridge 1998), or an empirical model, such as an artificial neural network (Kreider and Haberl 1994). In addition to providing a baseline for future performance, first principles models can also be used to identify more efficient operating strategies. Detailed first principles models tend to be over-parameterized for the measurements that are available in practice, suggesting that simplified first principles models may be more appropriate. This approach is discussed in a later section. In the fourth case, use of a whole building simulation program is the natural method of representing intended performance. Comparison of actual and intended performance can be made either during commissioning or during routine operation.

In the second, third and fourth cases, comparisons of energy use, peak demand and comfort conditions can be made on time-scales ranging from hours to weeks.

In general, a longer time-scale results in greater accuracy of the prediction but less information that may be useful in diagnosing the nature of any faults or problems.

An interesting example of the third case, but on a longer time-scale, is a particular office building in Oakland, California. The design-build contract for the construction was let on the basis of a DOE-2 model of the planned building. The contractor stood to gain or lose up to $250,000, depending on the performance of the building during the second year of occupancy as compared to the expected performance defined by the DOE-2 model (Stein et al. 2000).

There are, however, difficulties in using models intended for use in design to predict the performance of real buildings, including:

- Lack of the necessary input data
- Limitations of the model, which usually take the form of assumptions of idealized behavior of the envelope, mechanical equipment or controls

These difficulties are now discussed. Implementation issues are addressed later in the paper.

INPUT DATA

Heating and cooling energy consumption depends on building characteristics, occupancy, operational schedules, type of HVAC system, weather and other parameters. When the aim is to compare actual performance with the performance expected by the designer, the role of simulation is to correct for factors such as occupancy, internal gains and weather that are beyond the control of the designer. A major area of uncertainty is the calculation of heating and cooling loads; specific uncertainties include:

Solar Gain

- Insolation measurement: Individual buildings generally do not have an on-site solarimeter. There may be a weather station nearby; even then there can be problems with getting the data in real time and with data quality.
- Effect of surrounding buildings: In addition to shading, reflection may also be important, especially in downtown areas. A detailed approach to modeling this phenomenon is described in Reilly et al. (1994).
- Blinds: Manual operation is difficult to model.

The importance of estimating solar gain accurately depends on the type of building. A local measurement of insolation is most important for a shallow-plan building with large areas of relatively clear glazing.

Internal Gains

- Plug loads: Electrical submetering is only available in a few existing buildings; it can be installed more easily if planned for during design.
- Lighting: Again, measurements are made in a few existing buildings; they can be made more easily if planned for during design. Complications are introduced by air-handling luminaires and by outside lighting on the same circuits as inside lighting.
- Occupants: It is only possible to measure occupant numbers in certain situations, e.g. where there are time clocks, security cards etc. Metabolic rate and location in a particular thermal zone must be assumed

In the absence of measurements, plug loads can be estimated from nameplate ratings. In one case study (Wilkins 1998), the measured maximum consumption of each item of equipment was ~50% of the nameplate rating and the diversity factor was ~2. Alternatively, the internal gain may be estimated by using measured whole building electricity consumption. This approach may also significantly over-estimate the heat gain since a large fraction of whole building electricity use, such as that used by pumps, exhaust fans, elevator motors, and air compressors, may be converted to heat in non-conditioned spaces, such as mechanical rooms, basements, and penthouses. Even the heat generated in the conditioned space may not become cooling load if air-handling luminaires are installed since some of the lighting energy is picked up by the return air and some of that energy is carried out directly to the outside by the exhaust air.

Given these sources of uncertainty in the estimation of heating and cooling loads, there are three possible approaches:

1. Installation of the necessary instrumentation in the building, e.g., a solarimeter, electricity sub-meters, to provide measurements of the inputs required by conventional, first principles, simulations in order to calculate heating and cooling loads. A sensitivity study for the building in question is required to estimate the accuracy required for each type of measurement.
2. The ‘calibrated simulation’ approach, in which an empirical model of heating and cooling loads is calibrated by adjusting the values of its parameters so as to minimize the differences between the predicted and measured performance of the building over a period when the performance is deemed to be acceptable.
3. Direct measurement of the heating and cooling loads. For air systems, the load on the HVAC system can be determined by measuring the supply air-flow rate and the supply air and return air temperature and humidity.

The second and third approaches allow a first principles HVAC system model configured from design data to be used even when measurements of the boundary conditions required by a first principles model of the heating and cooling loads are not available.

CALIBRATED SIMULATION

The calibration process compares the results of the simulation with measured data and "tunes" the simulation until its results closely match the measured data. Systematic calibration of building models has been reported by a number of researchers dating as far back as 20 years (Diamond and Hunn 1981, Holtz 1990, Kaplan et al. 1992, Pratt 1990). The early calibration efforts focused on matching the monthly totals for the simulated heating and cooling consumption to the measured monthly electricity and gas utility bills. However, there are typically more simulation inputs that can be varied than measured data points. This severely limits calibration accuracy. More recent research on the calibration process has focused on comparing hourly measured data with simulation because the results represent the building dynamic energy characteristics in a more accurate and reliable way (Bou-Saada and Haberl 1995, Bronson et al. 1992, Haberl et al. 1995, Haberl and Bou-Saada 1998). Graphical and statistical comparison techniques are used to examine the fit between the thousands of data points being compared. Simulations based on the ASHRAE Simplified Energy Analysis Procedure (Knebel 1983) have been calibrated using daily data (Knebel 1983, Liu et al. 1998) and successfully used as part of a diagnostic process.

MODELING ISSUES

Zoning

Model simplification, which limits input detail to items that have a detectable impact on the measured energy use, is highly desirable to reduce the effort, and the ambiguity, associated with model calibration. Forms of simplification include the use of lumped, rather than explicit, representations of the building envelope and reduction in the number of zones that are modeled. Knebel (1983), Katipamula and Claridge (1993) and others have found that buildings can often be adequately treated as two zones: core and perimeter. A case study based on this approach, presented by Liu and Claridge (1995), showed very accurate results. An air side simulation program (Liu and Claridge 1995) has been developed using the two-zone model. The simulation program has been used to calibrate the system model, identify system operational problems and optimize system operation by two of the authors (DC and ML) since 1993. This experience indicates that the two-zone model works well provided the interior and exterior zones are properly determined. In the case of open-plan spaces, a good rule of thumb is that the perimeter zone extends 6 m (20 ft) in from the exterior surface.

Imperfect Operation of Mechanical Equipment

Even the more detailed whole building simulation models are generally based on idealized models of building and system performance. These idealizations are another important factor in the discrepancies that are often seen between simulation results and measured performance. A simulation model must be able to treat the departures from ideal behavior that occur in real systems if it is expected to portray system performance accurately. The question as to whether particular operation is considered acceptable or faulty varies from case to case. In practice, a fault that is not considered important enough to fix is considered acceptable and models of real building operation need to be able to treat this type of operation. Some examples follow; further details are given by Liu et al. (1998):

- <u>VAV Terminal Box:</u> A VAV box modulates the airflow rate to maintain room temperature and/or minimize the reheat. Idealized models assume that the box can reduce the flow rate to the design minimum value but a combination of poor damper quality and high static pressure at the box may limit the turndown that is achieved in practice.
- <u>Dual Duct Terminal Boxes:</u> Under full cooling conditions, the pressure on the hot air damper is high because there is little pressure drop between the fan and the terminal box because the hot air flow rate is small. This high pressure often results in significant leakage through the damper, resulting in simultaneous heating and cooling. A similar problem arises with leakage through the cold air damper under full heating conditions.
- <u>Coils and Control Valves:</u> Most simulation programs assume that coils and control valves can maintain the temperature reset schedules, which involves maintaining control of off-coil air temperature over the complete range of load. This assumption breaks down when the coil load is 20% or lower. Most control valves have a turndown range of 20:1 to 40:1; if the valve has an authority of 0.5, the minimum predictable flow varies from 5% to 10% of range which, because of the non-linear relationship between water flow rate and load, corresponds to ~10-20% of full load. In addition, there is almost always significant leakage in real systems. Under high cooling loads, hot water leakage is increased due to increased differential pressure across the hot water control valve. During high heating loads, the chilled water leakage is high due to increased chilled water differential pressure across the chilled water valve. Pre-heat coils often heat up the supply air by 3°F or more during summer months if hot water or

steam is supplied to the coil. The re-heat coil may also warm the supply air 3°F or more during full cooling mode due to leakage.

Thus, models that seek to represent the behavior of real systems should be able to account for imperfect control of supply air temperature and flow rate and for simultaneous heating and cooling. The magnitudes of these effects are case-specific and the model parameters that define these magnitudes need to be identified from the measured performance.

Controls

Another limitation of current whole building simulation models is their inability to model real control strategies, even generically. Controls are modeled in an idealized way:

- Local loop behavior is not modeled:
  - Whereas some HVAC processes are quite fast, there are some that have dominant time constants of 10 minutes or more: room temperature control, chilled water and condenser loop latencies (transport delay in piping systems, capacity of cooling tower sumps);
  - Proportional control is often used for most of the HVAC components in an old system while the simulation assumes ideal control. Actual temperatures, including room temperatures, are then significantly offset from their set-points under most operating conditions.
- The effect of equipment cycling on control and efficiency is not directly modeled.
- Reset strategies are often implemented with low gain integral control, which leads to relatively a sluggish response, rather than the instantaneous response assumed in whole building simulation programs.

ON-LINE IMPLEMENTATION

The first part of the paper has addressed some of the information and modeling issues that arise when using whole building simulation programs as reference models of correct operation for the assessment of building performance. The remainder of the paper addresses some of the implementation issues that arise in on-line implementation to support real-time performance assessment.

Performance assessment can either be:

- Passive—data from routine operation are analyzed for evidence of faults
- Active—test signals are generated by the performance assessment software and transmitted to the building control system in order to exercise the building and hence acquire data that cover a wide range of the operating space

Passive monitoring has the advantage of being non-intrusive and can be performed on-line or off-line. However, its diagnosis capabilities are limited by the fact that the data from different regions of the operating space usually needed to distinguish between different faults may have been collected over a significant period of time, during which the fault condition may have changed significantly, confusing the diagnosis. Passive monitoring only requires one-way communication between the performance assessment software and the building control system, as shown in **Figure 1a**. The data transmitted by the building control system include the meteorological measurements and other boundary conditions for the simulation, together with measurements of electric power, temperature, flow rate etc for comparison with the predictions of the simulation.

Active testing can significantly alter the comfort conditions in a building and hence is usually performed when the building is unoccupied, either prior to handover or during evenings or weekends. It must be performed on-line and requires two-way communication between the performance assessment software and the building control system, as shown in **Figure 1b**. The data transmitted by the performance assessment software include the set-point changes required to drive the building and its systems to different parts of the operating space.

Performance assessment for building systems is generally more concerned with the steady state performance, at least for equipment, and so there is usually no real need for synchronous communication, it being sufficient for the performance assessment

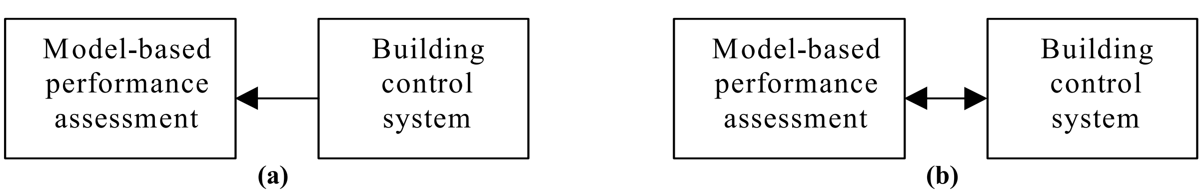

Figure 1. Data transfer requirements between (a) passive monitoring and (b) active testing.

system and the building control system to be independently synchronized to real time. A different but related application where synchronous communication may be required is where two simulation environments are coupled at run-time and the aim is to run the coupled simulation as fast as possible. Having defined the basic communication requirements, the paper now addresses software architecture and communication protocol issues.

COMMUNICATION BETWEEN SIMU-LATIONS AND CONTROL SYSTEMS

Modern building control systems, especially those in larger buildings, have a hierarchical structure and typically use different communication protocols at different levels, as shown in **Figure 2**.

The lowest level of communication could take place with unitary local-loop controllers. Interfacing at this level would require the use of analog to digital (A/D) and digital to analog (D/A) converters so that simulated variables could be transformed into physical variables such as voltage and vice versa.

Communication protocols such as BACnet (ASHRAE 1995) and LonWorks are primarily focused on lower level control networks comprised of controllers such as room thermostats, AHU controllers, VAV controllers, etc. OPC - Object linking and embedding for Process Control (OPC 2001) is an application-level interfacing standard that would apply at the LAN networking level. XML and other Internet protocols apply to the campus-wide or global level. Although, the division between the different levels is often blurred, it is apparent that there are now various standards and protocols to cover all levels in a building control system hierarchy.

Having a distributed and object-based simulation program greatly simplifies interconnection between the components within a simulation and with a real building control system. **Figure 3** illustrates how different parts of what could be one simulation program or multiple separate simulation programs connect to a real system. It should be noted that each level in the hierarchy that was depicted in **Figure 2** provides access to the levels below. For example, a whole building simulation connected through the Internet to a real control system could access information at the unitary controller level and could even simulate equipment at this level. However, the full realism of simulating a low-level entity by means of a simulation at a higher level would be restricted to real controllers at the same higher level as the simulation. Moreover, attempting to achieve low-level emulation through simulation interaction at higher levels may prove prohibitive due to network bandwidth and processing constraints. Hence, simulation that is based on a distributed architecture and has interfaces at multiple levels provides the greatest opportunity and flexibility in creating cybernetic building systems.

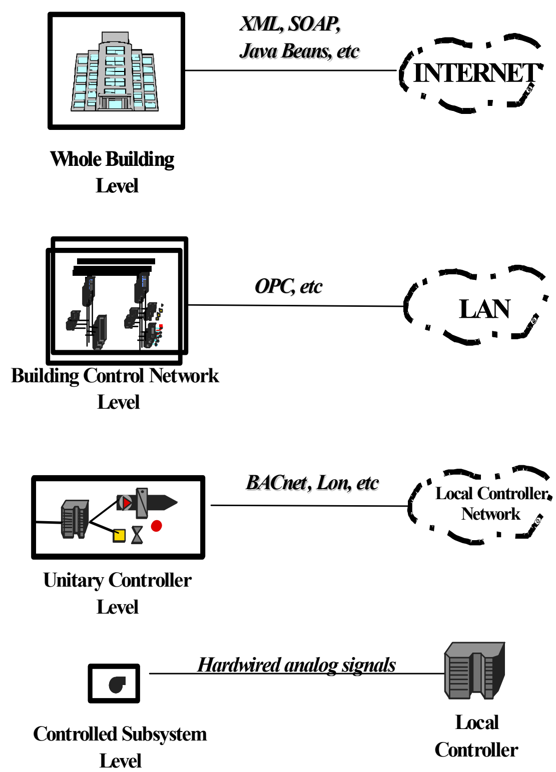

Figure 2: Multi-level communication protocols.

One of the barriers to linking analysis software, such as energy simulation, to building control systems has been the difficulty in engineering the communication interfaces required for data exchange using proprietary EMCS protocols. Application to a different EMCS often requires significant re-engineering effort and possibly the development of gateways that act as translators from one protocol to another. The availability of standardized protocols and object representations is beginning to alleviate the engineering burden of developing the communication aspects of exogenous EMCS applications such as real-time simulation. The synergy of EMCS object standards and simulation modeling information requirements and the apparent convergence of these two areas under umbrellas such as the International Alliance for Interoperability (IAI http://www.iaiweb.lbl.gov/) is creating opportunities for the development of "plug and play" functionality.

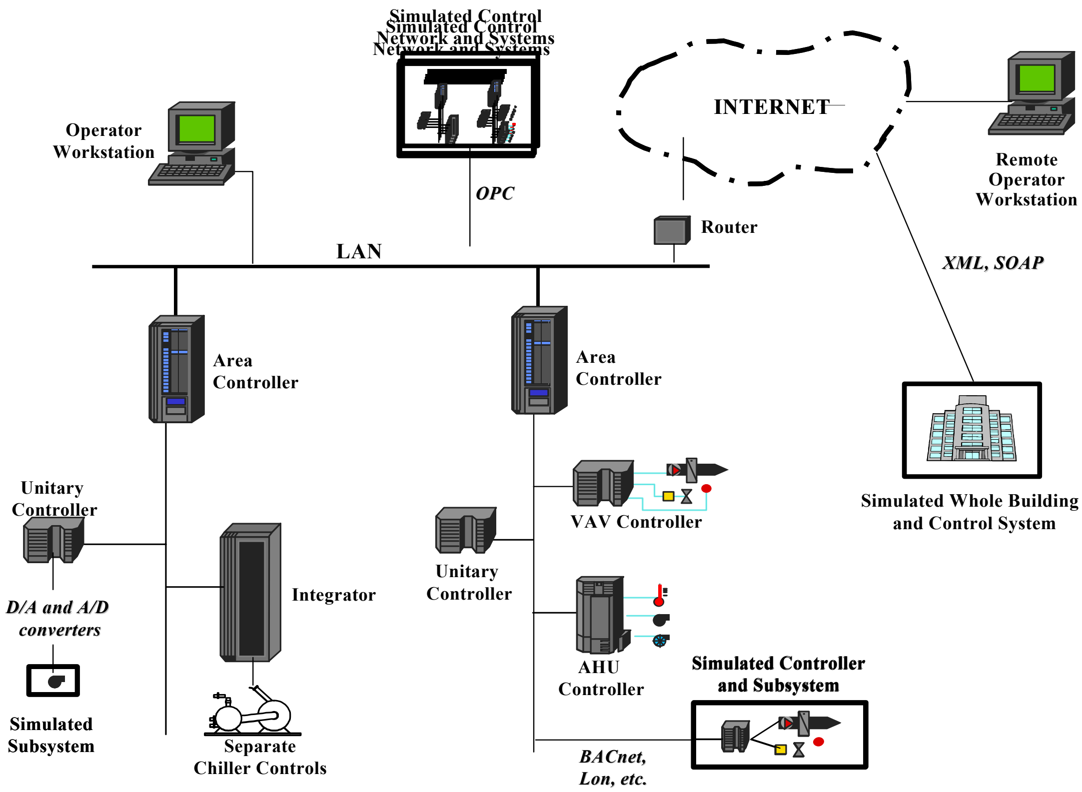

Figure 3. Multilevel simulation interaction with a typical building control system.

Distributed Objects

Figure 4 shows the benefits of a software architecture built around the concept of distributed objects (Orfali et al. 1996). ORB is an object request broker. COM/DCOM and CORBA are types of object request brokers. Interfaces are the external representations of objects. The form of an interface is dependent on the type of ORB that is used. OPC is a COM/DCOM interface specification. The types of objects used in a distributed architecture are sometimes termed “components” in order to distinguish them from “programming objects” such as C++ classes.

Although client/server terminology is still used in the case of distributed component architectures, the division between client and server is often blurred. Typically though, components are viewed as servers, capable of performing some function and being able to share that functionality through their interfaces. Clients do not usually need to expose any functionality and would normally just access the services of components’ servers. Clearly, components could have server and client capability.

.Object-Based Simulation Example

Figure 5 shows an example of a distributed simulation platform that will allow a simulation to be broken into different parts and executed in separate processes. Three separate processes handle the simulation of a building, its HVAC system and control applications. Each simulation object is

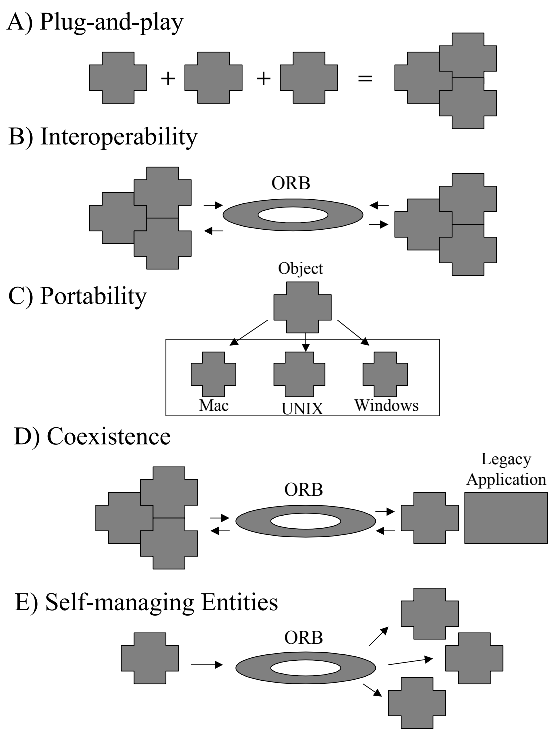

Figure 4. Benefits of distributed objects.

capable of interfacing to real hardware and this could take place at any of the hierarchical levels that were depicted in **Figure 2**..

Aside from interfacing and communication aspects, distributed simulation requires coordination between the disparate objects in terms of timing and data exchange management. For example, the data associated with one set of objects may be needed as boundary conditions in another. Coordination of the simulation objects requires either synchronization to one particular simulation object or to real time. The possibility of different simulation time-steps or controller sampling intervals for each object requires communication of information between dependent objects so that the state of a particular object can be informed or interrogated. In this scenario, the concept of software "agents" could be introduced to describe the distributed and cooperative nature of this type of simulation architecture (Oliveira et al., 1999).

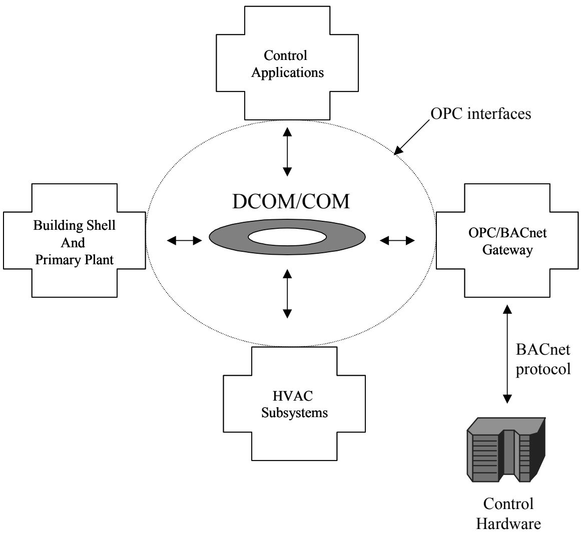

Figure 5. Object-based simulation.

CONCLUSIONS

Whole building simulation programs have the potential to act as reference models of correct operation for use in the performance assessment of real buildings. Additional sensors, over and above those usually installed in energy management and control systems, as needed to provide the necessary input data. Alternatively, calibrated simulations can be used to predict current performance from previous performance.

The standard communication protocols that are starting to be adopted in the building controls industry have the potential to be used to interface on-line simulation programs to energy management and control systems. Object-based methods provide a mechanism for defining the standard interfaces that are required for "plug'n'play" interoperability of simulation and control software components but more work is needed to break the functionality of simulation programs into distributed components.

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HPCBS

High Performance Commercial Building Systems

Potential of On-line Simulation for Fault Detection and Diagnosis in Large Commercial Buildings with Built-up HVAC Systems

Element 5 - Integrated Commissioning and Diagnostics
Project 2.3 - Advanced Commissioning and Monitoring Techniques

Energy Systems Laboratory, University of Nebraska
Energy Systems Laboratory, Texas A&M University

June, 2002

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Prepared by:

Energy Systems Laboratory, University of Nebraska

And

Energy Systems Laboratory, Texas A&M University

For:

Lawrence Berkeley National Laboratory

June 2002

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DISCLAIMER

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1. EXECUTIVE SUMMARY

Typical buildings consume 20% more energy than necessary due to inefficient operational procedures, non-optimal control schedules, and system faults. To realize this potential for energy performance improvement, the system faults must be detected, the mechanical and electrical problems diagnosed, and optimal control schedules and operating sequences developed and implemented. Today, these tasks must be conducted by well trained engineers using field measurement, specialized engineering analysis, and testing. Due to a lack of engineers skilled in operational optimization and the length of the process, performance optimization has been limited to a small fraction of the building stock. Consequently, excessive amounts of energy are wasted daily in existing buildings.

Simulation programs, such as DOE-2 and BLAST, are sometimes used for building system sizing and optimization during the design phase. More recently, other software programs, such as AirModel, have been developed to identify system faults, diagnose problems, and optimize system operation in existing buildings.

This report presents the results of a study of the potential for using simulation programs for on-line fault detection, problem diagnosis, and operational schedule optimization for large commercial buildings with built-up HVAC systems.

This study reviewed over a dozen simulation programs and determined that AirModel and EnergyPlus were most suitable for initial use in the on-line simulation applications that are the focus of this study. Relevant characteristics of these programs include the following:

(1) EnergyPlus is a detailed system performance simulation program. It can perform detailed load and system performance simulation.
(2) AirModel is a simplified system performance simulation program. It can perform simplified load and detailed system performance simulation. It differs from EnergyPlus in the level of detail of the building load modeling, including the number of zones. It allows the modeling of actual system performance, such as leaking dampers.
(3) Both EnergyPlus and AirModel have the capability to: (a) identify in-efficient operation at the whole building level, (b) identify major time invariant mechanical systems, (c) develop improved and optimized operational and control schedules and set points, and (d) project potential energy savings.
(4) Both EnergyPlus and Airmodel can be used for on-line simulation and fault detection after revising the input structures of the program.
(5) Airmodel can be embedded in existing energy management and control systems. On-line simulation can be conducted without major revision to the program.

Two case studies in which AirModel was used off-line to identify and diagnose system problems at the whole building level are presented. These cases studies illustrate to potential value of on-line simulation.

Two phase demonstration of on-line simulation is recommended. During the first phase, a commercial building will be selected. The building energy consumption and weather data will be measured in real time. AirModel will be run in parallel to the building operation. An interface will be developed to integrate the building automation system and AirModel input and output. Faults will be identified using discrepancies between the measured and simulated energy consumption. A manual of simulation based functional test procedures will be developed.

During the second phase, EnergyPlus will be used to identify building level faults as conducted in the first phase by AirModel. Currently, a number of system models are not developed for EnergyPlus. AirModel will be used to identify the system level faults, such as AHUs, chillers, and boilers. The potential and capabilities of the simulation based functional test will be documented based on the field application. A manual of fault diagnosis procedures will be developed for use with simulation programs.

2. BACKGROUND AND OVERVIEW OF POTENTIAL FOR DETECTING AND DIAGOSING FAULTS USING ON-LINE SIMULATION

There is an increasing realization that many buildings do not perform as intended by their designers. Reasons include faulty construction, malfunctioning equipment, incorrectly configured control systems and inappropriate operating procedures. Changes in the use or configuration of buildings without corresponding changes in systems or operating practices often contribute to these problems. Occasionally the problems are caused or compounded by design errors.

The first step in detecting and diagnosing such problems is the evaluation of building performance. A quantitative evaluation of performance requires a baseline or reference, against which to compare the actual performance. Possible sources of such a baseline include:

1. The previous performance of comparable buildings
2. The current performance of comparable buildings
3. The previous performance of the building in question
4. The intended performance of the building in question

In the first case, the performance of the building in question is compared to that of similar buildings using a database of the actual performance of a statistically selected sample of comparable buildings. The comparison is usually made in terms of whole building electricity and fuel consumption. This 'benchmarking' process can provide an approximate assessment of relative performance from very modest input data, typically building type, floor area and geographical location. Benchmarking is a useful screening tool, allowing attention to be focused on those buildings that appear to be performing poorly (add references).

In the second case, campuses or chains of comparable buildings with suitable monitoring capabilities may be compared on the time-scale of an hour to a week to detect the onset of operational changes or malfunctions that have a significant effect at the whole building level (reference?). This quasi-real-time form of benchmarking provides a relatively simple method of detecting significant degradations in performance before the cumulative effects of that degradation become severe.

In both the first and second cases, simple regression models are typically used to correct for differences between the conditions under which the actual performance is observed and the conditions for the baseline. However, simulation models are starting to be used as interpolation tools for more sophisticated benchmarking where more information about the buildings and their energy systems is available.

In the third case, the previous performance can be represented using a 'calibrated simulation', in which the parameters of the model are adjusted to minimize the difference between the predicted and measured performance over a selected period. The model can either be a detailed first principles model, such as EnergyPlus (Crawley et al. 2000), DOE-2 (LBNL 1982) or ESP (ESRU 2000), a simplified first principles model, such as AIRMODEL (Liu and Claridge 1998), or an empirical model, such as an artificial neural network (Kreider and Haberl 1994). In addition to providing a baseline for future performance, first principles models can also be used to identify more efficient operating strategies. Detailed first principles models tend to be over-parameterized for the measurements that are available in practice, suggesting that simplified first principles models may be more appropriate. This approach is discussed in a later section.

In the fourth case, use of a whole building simulation program is the natural method of representing intended performance. Comparison of actual and intended performance can be made either during commissioning or during routine operation. In the second, third and fourth cases, comparisons of energy use, peak demand and comfort conditions can be made on time-scales ranging from hours to weeks. In general, a longer time-scale results in greater accuracy of the prediction but less information that may be useful in diagnosing the nature of any faults or problems.

The second step is to identify the faults in a building by comparing the intended performance with the actual performance. This requires that the actual energy consumption (such as whole building electricity, heating, and cooling energy consumption) be measured along with weather and room conditions. These measurements are compared with the baseline performance and any differences analyzed to determine the faults.

The third step is to diagnose the problems if the measured performance differs from the expected or predicted performance. This can be accomplished by using one or more of the following approaches:

1. Inspect building and measure major building operational and control parameters, such as system operation schedules, supply water temperatures, supply air temperatures, etc. to identify faults
2. Conduct numerous short term measurements with dedicated meters. Input measured parameters to a specialized system model(s) or component model(s) to identify possible problems.
3. Calibrate baseline model(s) to match the simulation output to current measured energy performance data by adjusting input and operational parameters.

The first approach can identify major mechanical and electrical problems, such as broken VFDs, and damaged valves or dampers. If engineers conduct the field inspection, the control sequence may be checked as well. However, it is often hard to identify problems that only occur under different operating conditions. For example, it is hard to identify a leaking hot water valve if the inspection is conducted during winter when the valve is controlled open or it will be hard to detect chilled water hunting if the inspection is conducted during summer when the system is not hunting.

The second approach is useful for identifying problems with a particular component or set of components. This approach will be developed and integrated into Building Automation Systems (BAS) as the declining cost of sensors makes it practical.

The third approach requires that building energy consumption be measured. The building energy consumption can be measured using dedicated meters or meters installed as part of the BAS. The operational schedules, control parameters, envelope parameters, and or occupancy schedules are adjusted as physically appropriate in the input section of the baseline model. The baseline model results are then compared with measured consumption. If there are significant differences, building parameters and schedules are adjusted to match the simulation output with measured performance.

If the operational schedules in the original baseline model are changed to match the simulation with measured performance (energy consumption and room conditions), the deviation of the changed operation and control schedules from the original schedules is the cause of the poor performance. The fault or faults are diagnosed. This approach can be implemented from remote locations or on site. This approach can effectively locate the faulty devices and the nature of the problem(s). It can also identify historical problems and problems that occur under other weather and occupancy conditions, providing comprehensive system diagnosis capabilities.

The exact mechanical problems may not be identified explicitly. For example, this approach may identify a leaking control valve. But it may not determine whether the leakage is due to an excessive pressure difference or a stuck valve core. On-line simulation cannot entirely replace field inspection. A field visit should be performed to identify the problem and repair should be performed accordingly. Using simulation to assist in fault detection and diagnosis can maintain high building performance with minimum cost.

3. REVIEW OF SIMULATION PROGRAMS

A large number of simulation programs have been developed for building system design and/or design optimization. Some of them are more suitable for fault detection and diagnosis than others. This section reviews the simulation programs available with particular attention to features needed for fault detection and diagnosis.

DOE lists over 100 building energy simulation programs on its website (http://www.eren.doe.gov/buildings/tools_directory/database). Appendix A presents brief summary information for 16 selected programs as shown in Table 3-1.

Table 3-1. The 16 programs reviewed for use in on-line simulation of large buildings.

		Detailed general purpose detailed whole building energy simulation programs
1	APACHE	thermal design, thermal analysis, energy simulation, dynamic simulation, system simulation
2	BLAST	energy performance, design, retrofit, research, residential and commercial buildings
3	DOE-2	energy performance, design, retrofit, research, residential and commercial buildings
4	EnergyPlus	energy simulation, load calculation, building performance, simulation, energy performance, heat balance, mass balance
5	HAP v4.0	energy performance, load calculation, energy simulation, HVAC equipment sizing
6	TRACE 700	energy performance, load calculation, HVAC equipment sizing, energy simulation, commercial buildings
7	VisualDOE	energy performance, design, retrofit, research, residential and commercial buildings
		Simplified general purpose whole building energy simulation programs
1	AirModel	Building commissioning, fault detection, and savings evaluation
2	ASEAM	energy performance, existing buildings, commercial buildings
3	System Analyzer	energy analyses, load calculation, comparison of system and equipment alternatives
		Specialized building energy simulation programs
1	HBLC	heating and cooling loads, heat balance, energy performance, design, retrofit, residential and commercial buildings
2	HVACSIM+	HVAC equipment, systems, controls, EMCS, complex systems
3	SPARK	object-oriented, research, complex systems, energy performance
4	TRNSYS	design, retrofit, research, energy performance, complex systems, commercial buildings
		Data visualization/analysis programs
1	ENFORMA	data acquisition, energy performance, building diagnostics, HVAC systems, lighting systems
2	Visualize-IT Energy Information and Analysis Tool	energy analysis, rate comparison, load profiles, interval data

The simulation programs reviewed that are suitable for use on large commercial buildings are categorized in the table into the following groups:

1. Detailed general purpose building energy system simulation programs, which simulate both building envelope and HVAC systems.
2. Simplified general purpose building energy system simulation programs, which simulate both building envelope and HVAC systems.
3. Specialized building energy simulation programs which may be intended primarily for research purposes, or may simulate only part of the building, such as the loads.
4. Data visualization programs that are intended primarily for viewing or analyzing measured energy consumption data.

A simulation program capable of simulating the complete building system is required to detect and diagnose HVAC system faults since both building thermal loads and systems must be simulated during the process. Hence, only the programs in shown in the first two categories are suitable for the on-line fault detection application to be investigated. The best candidate within the detailed model-based simulation programs is EnergyPlus, since it has the following features:

1. Users can set the simulation time-step and the simulation period. For example, a particular fault detection process may only require several hours of simulation instead of a whole year. The time-step can vary from one minute to one hour. This is useful for detecting dynamic problems.
2. Users can construct any system using basic blocks. Most other programs can only simulate pre-defined systems, which are often incapable of representing the actual systems in buildings.
3. Users can select individual output parameters. This is helpful in analyzing the results.
4. EnergyPlus has (or will have) all the features of DOE-2 and BLAST and includes some features of TRNSYS and similar programs.

EnergyPlus is also a public domain program, which means that documentation of algorithms used is available.

The main candidates among the simplified simulation programs are ASEAM and AirModel. AirModel is specifically designed for fault detection and building commissioning; the following features make it the best choice for on-line application:

1. Actual system performance can be simulated. For example, air leakage in terminal boxes can be simulated.
2. A good graphic interface for the output makes comparison of measured and simulated results easy.
3. Input requirements are very simple.

Review of EnergyPlus

EnergyPlus is a new program, although based on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus largely comprises new, modular, structured code written in Fortran 90. It is primarily a simulation engine - it is intended that user interfaces will be developed by the private sector. Input and output are simple, comma-separated, ASCII text files and the input language are much simpler than those of DOE-2 or BLAST.

EnergyPlus contains detailed system and load simulation models. Most common systems can be simulated using EnergyPlus. Its accuracy is expected to be similar to, or better than, DOE-2 or BLAST.

The modular structure is the most significant advantage of EnergyPlus over DOE-2 or BLAST. This feature makes it the best simulation program for building fault detection and diagnosis applications for the following reasons:

- Engineers can add or modify modules to reflect actual system performance, such as terminal box leakage rate. Consequently, it has the potential to predict actual system behavior instead of only the “ideal behavior” simulated by most programs, so real faults can be identified. An idealized simulation can identify a deviation from ideal behavior, but cannot simulate the non-ideal behavior of many typical faults.

- Engineers can use the energy meter feature to categorize the energy consumption by type, resources, and systems. Energy inefficiency can be identified by comparing the utility bills or BAS measured energy consumption data with simulated energy consumption data.
- EnergyPlus allows the specification of any simulated parameters as outputs, such as chilled water return temperature and chilled water flow rate. Engineers can specify BAS measured parameters as output parameters in the EnergyPlus program. The simulated data can be compared with BAS measured data. Most system faults can be identified easily if modeling and measurement errors can be quantified.
- EnergyPlus makes it easy to simulate part of a building. For example, air handling units can be simulated using a dummy central plant. This feature (1) minimizes the simulation effort, (2) decreases cost, and (3) allows detailed trouble shooting in local areas or systems.
- EnergyPlus allows the user to specify the simulation time-step. Engineers can use this feature to identify peak demand control problems and develop improved demand control strategies. This feature will also allow engineers to identify dynamic mechanical and control problems, such as damper hunting, since EnergyPlus will model load changes but not control system instability.
- EnergyPlus allows flexible weather data input. Users can create their own weather data files using specified formats. This allows fair comparison of measured consumption and simulated consumption.
- EnergyPlus is a simulation engine and input files will be hard to create and manage until graphic interfaces are developed. An interface intended for building operation applications should have special features for fault detection and diagnosis purposes since the input and output requirement are very different from the requirements for building design and design optimization.

Review of AirModel

AirModel is a software package developed for use in the building continuous commissioning and optimization process at the Energy Systems Laboratory, Texas A&M University (Liu 1997). Currently, the Energy Systems Laboratory at the University of Nebraska maintains and updates the program. It simulates building heating, cooling, and electricity consumption when provided with suitable building information and weather (dry bulb temperature and wet bulb temperature or relative humidity) data. It identifies system faults by comparing the simulation results with measured results, and optimizes the system operation schedule automatically. It accepts data of any time interval, such as hourly, daily, or monthly, and can also be used with bin weather data. A program called Voyager, developed at Washington University (Lantern 1990), is used as the primary graphic interface to explore simulation results.

AirModel was developed by drawing on the extensive engineering experience of the Continuous Commissioning group at the Energy Systems Laboratory at Texas A&M University. The first version was completed in 1993 and Version 6 was completed in 2000 at the Energy Systems Laboratory, University of Nebraska. AirModel has been used by its developers since 1993 to identify operation and maintenance problems.

AirModel is a system-based simulation program. The part of the building served by a single AHU is simplified into one or two zones. It treats all the major AHU configurations: (1) dual duct systems, (2) single duct with terminal reheat, and (3) single zone systems. It can simulate both variable air volume and constant air volume systems. The pre-heat coil can be placed in either the mixed air stream or outside air stream. The outside air can be directly introduced into an AHU or be pre-treated using a dedicated unit. The heating coil can be placed either before or after the cooling coil for single zone units. Multiple AHUs can be simulated using AirModel.

AirModel requires the following input: outside air conditions and measured energy consumption, and building and system information. Table 3-2 lists the weather and energy input parameters required.

Table 3-2: Description of Weather and Energy Input File

Column	Definition	Note
1	Site number	Any integer number
2	Month	Integer number from 1 to 12
3	Day of the month	Any integer number from 1 to 31
4	Year	Integer number
5	Decimal year	Any real number
6	Julian Year	Real number
7	Hour	Any number from 0 to 23 or from 0 to 2300
8	Dry bulb temperature (°F)	Real number
9	Dew point temperature (°F) or Relative humidity (0 to 1)	Real number
10	Measured chilled water consumption (MMBtu/hr)	Real number
11	Measured hot water consumption (MMBtu/hr)	Real number

The building is characterized using 36 envelope and system inputs or schedules for each AHU and 19 inputs or sets of component characteristics for the plant.

AirModel conducts a detailed energy and indoor comfort simulation. It reports 43 categories of variables (See Table 3-3 for the output variable list), including airflow to each zone and through each duct, CO2 level in each zone, and energy consumption.

The graphical interface and simplified input information allow quick calibration of the simulation model. This is one of the major advantages of AirModel over DOE-2 or similar programs. The graphic interface can present each parameter in both time series and scatter plots. Any two parameters can also be compared in time series and scatter plots. Figure 1 is a typical screen used in the model calibration process. The simulated and measured chilled water energy consumption are compared using both time series and scatter plots.

AirModel uses a simplified model to estimate building thermal loads. The effect of thermal mass is estimated using representative room weighting factors. It has good simulation accuracy for daily and hourly simulation since envelope thermal loads typically have a very limited impact on the building thermal energy consumption in large office buildings

Table 3-3: Summary of AirModel outputs

Column	Definition
1	Month
2	Day
3	Year
4	Hour
5	Day of Week
6	Ambient Temperature ^oF
7	Ambient dew point (^oF)/relative humidity (%)
8	Measured chilled water consumption (MMBtu/hr)
9	Measured hot water consumption (MMBtu/hr)
10	Measured whole building electricity consumption (kWh/h)
11	Simulated chilled water consumption (MMBtu/hr)
12	Simulated hot water consumption (MMBtu/hr)
13	Simulated whole building electricity consumption (kWh/h)
14	HVAC operation cost (Heating + Cooling + Fan Power) ($/hr)
15	Residue of simulated chilled water consumption (MMBtu/hr)
16	Residue of simulated hot water consumption (MMBtu/hr)
17	Residue of simulated whole building electricity consumption (kWh/h)
18	Supply fan power consumption (kWh/h)
19	Interior zone relative humidity (%)
20	Exterior zone relative humidity (%)
21	Interior zone CO_2 level (ppm)
22	Exterior zone CO_2 level (ppm)
23	Outside air intake fraction (%)
24	Cold air flow to interior zone (cfm)
25	Hot air flow to interior zone (cfm). Zero flow for SD systems
26	Cold air flow to exterior zone (cfm)
27	Hot air flow to exterior zone (cfm). Zero flow for SD systems
28	Cold deck temperature (^oF)
29	Hot deck temperature (^oF)
30	Mixed air temperature (^oF)
31	Pre-cooling coil temperature (^oF)
32	Pre-heating coil temperature (^oF)
33	Pre-cooling energy consumption (MMBtu/hr)
34	Cooling energy consumption of main cooling coil (MMBtu/hr)
35	Pre-heating energy consumption (MMBty/hr)
36	Heating (DD systems)/re-heating (SD systems) consumption (MMBtu/hr)
37	Chilled water supply temperature (^oF)
38	Main coil chilled water return temperature (^oF)
39	Pre-cooling coil chilled water return temperature (^oF)
40	Average chilled water return temperature (^oF)
41	Chilled water flow rate to the main coil (GPM)
42	Chilled water flow rate to the pre-cooling coil (GPM)
43	Total chilled water flow (GPM)

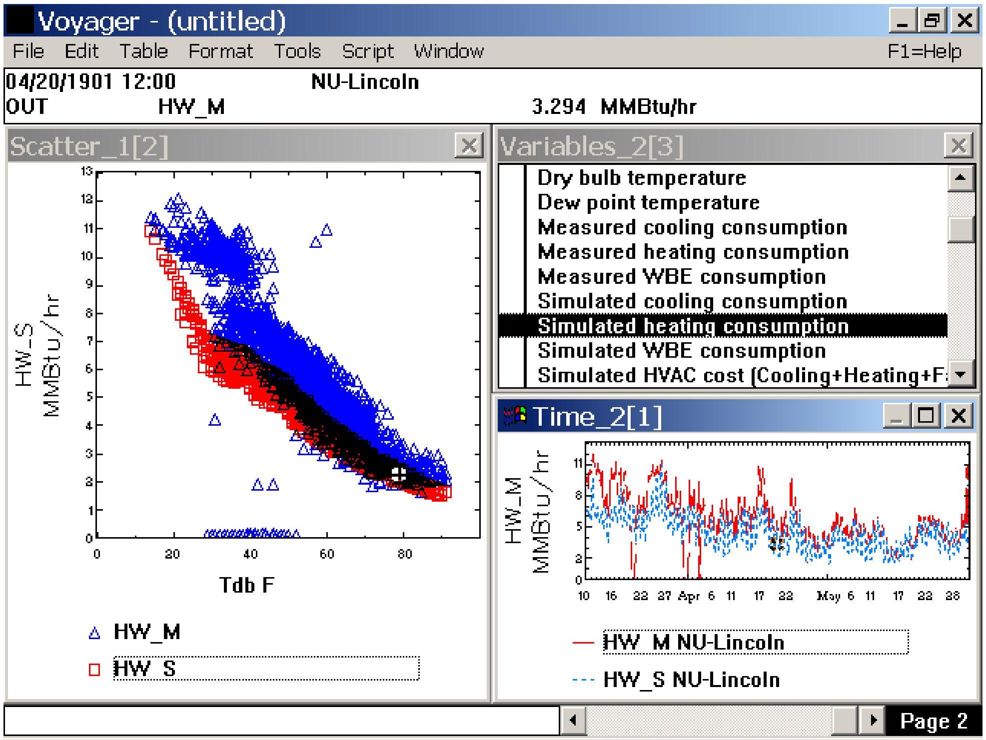

Figure 3-1: A Typical Screen during Model Calibration Process

4. DEMONSTRATION CASE STUDY I - DUAL DUCT AIR HANDLING UNITS

Building and HVAC System Information

The John Sealy South building is a 12-story in-patient hospital facility in Galveston, Texas with a total conditioned floor area of 298,500 ft^2. The building has light-colored brick walls with recessed windows to limit sunlight exposure. The windows make up only 7% of the wall area. The exterior zone of the building is occupied by patient rooms, while the interior zone contains nurses' stations and other types of office spaces.

Lighting and people are the major sources of internal gain for this building. Average lighting electricity consumption is 2.75 W/ft^2 and corridors are substantially over-lit. At night, most of the lighting in patients' rooms is turned off, while interior zone lights remain on.

There are four dual-duct constant air volume systems (Figure 4-1). The total design airflow is 302,000 CFM with 30% outdoor air intake. The building receives chilled water and steam from a central plant.

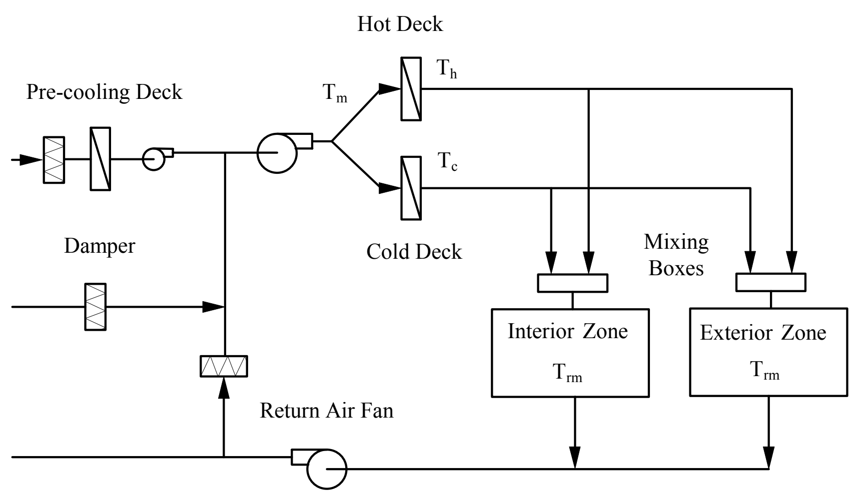

Figure 4-1: Schematic Diagram of Typical AHU System for John Sealy South Building

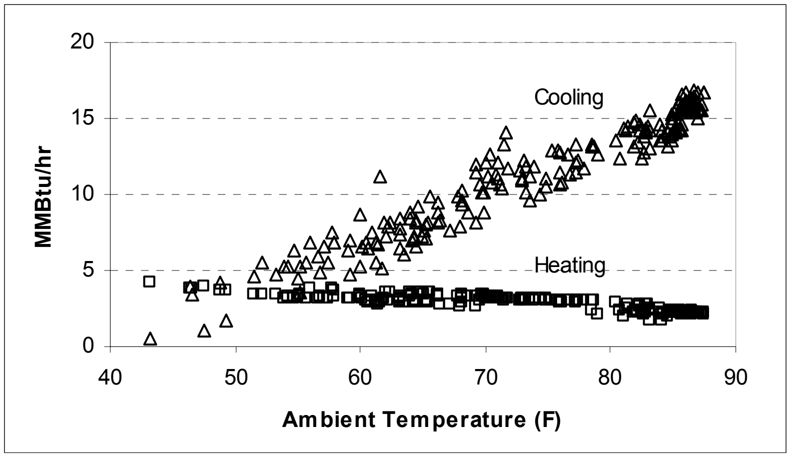

Figure 4-2: Measured Daily Average Chilled Water and Heating Water Energy Consumption Versus Ambient Temperature

Baseline Development

The baseline simulation model that represents the expected performance was developed using the envelope design information and the then current BAS control system set-points and schedules. Table 4-1 summarizes this information. The reference values of these parameters were collected during a site visit. No hourly weather data are available for Galveston, so measured weather data from an airport about 30 miles to the northwest were used for the case study. These data represent Galveston weather fairly well except during very hot summer days when the dew point temperature is 2°F to 3°F higher in Galveston. Most input parameters are determined from design drawings, air balance reports and reset schedules used by the BAS. Internal heat gain is estimated based on the measured electricity consumption of the lights and receptacles in the building and occupancy information. Solar gains are estimated using simple procedures suggested by Knebel [1983]; alternatively, those of Vadon et. al. [1993] may also be used. The effective values of the combined internal and the solar gains are then adjusted during model calibration, if necessary. When the gain values used are too low, the model will over-predict winter heating consumption and under-predict summer cooling consumption; the gains are then adjusted to more suitable levels. Infiltration is also difficult to determine by simple site observations. When the infiltration estimate is too low, predicted indoor humidity levels will be lower than measured values during humid weather. For other weather conditions, the infiltration may be assessed using the CO_2 level.

Table 4-1: Summary of Input Parameters

Symbol	Definition	Reference Values
T_o	Ambient dry bulb temperature	Houston Hobby Airport
T_{dp}	Ambient dew point temperature	Houston Hobby Airport
T_{rm}	Room temperature	72 °F
T_r	Return air temperature	77 °F
A	Total conditioned floor area	298,500 ft^2
f_{int}	Fraction of interior floor area to the total floor area	0.35
UA_{wall}	Total wall heat transfer coefficient	36,500 Btu/hr °F
UA_{win}	Total window heat transfer coefficient	16,000 Btu/hr °F
Q_{sol}	Solar heat gain	15,750 Btu/hr °F
$CFM_{inf,int}$	Air infiltration rate to the interior zone	0.2 ACH

$CFM_{inf,ext}$	Air infiltration rate to the exterior zone	0.4 ACH
q_i	Internal gain due to lighting and other equipment per unit floor area	2.42 W/ft^2
A_{pe}	Units of floor area for each person	120 ft^2
CFM	Total supply air flow rate	302,300 CFM
f_o	Outside air fraction	0.30
p_{fan}	Power consumption of the supply fan	625 hp
T_{pre}	Pre-cold deck set point	60 °F
T_c	Cold deck set point	55 °F
T_h	Hot deck set point	If T_o<80 °F then Min(90, 85-0.25(T_o-75) else 80 °F

The heating and cooling energy consumption from February 1993 through August 1993 was predicted using the reference values of input parameters. Figure 4-3 compares the measured and simulated heating and cooling energy consumption.

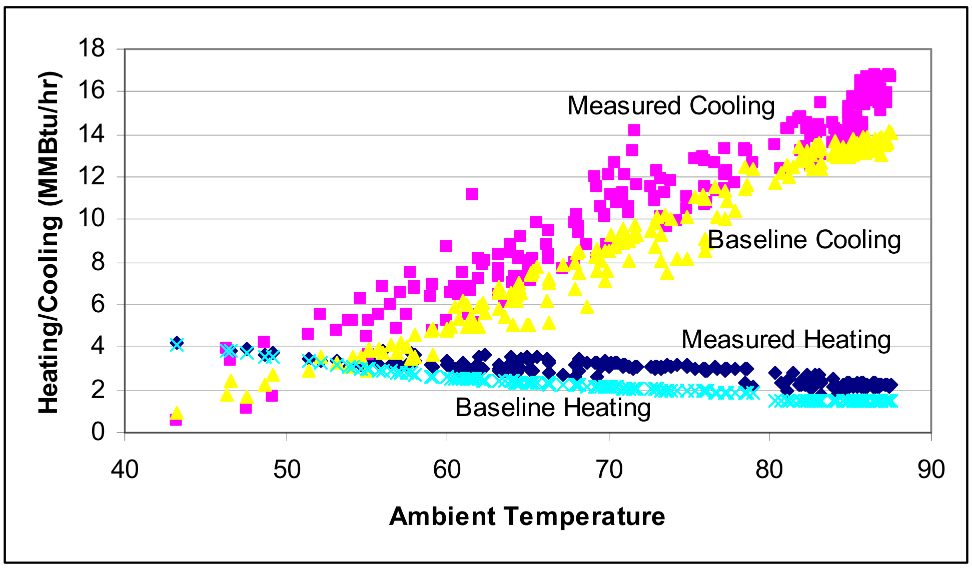

Figure 4-3: Simulated Baseline and Measured Heating and Cooling Energy Consumption

Fault Detection and Diagnosis

From Figure 4-3, the simulated baseline energy consumption values are 26% and 16% lower than the measured values for heating and cooling respectively. The HVAC systems are not functioning as designed.

Since both the simulated heating and cooling energy consumption are lower than the measured values, mass and energy balance indicated that the difference must have been due to: (1) the assumed total air flow rate being lower than the actual flow rate; or (2) the assumed cold deck temperature being higher than the real value or the hot deck temperature being higher than the assumed value, or both.

When the assumed total air flow is lower than the actual flow, the model will under-estimate both heating and cooling energy consumption by about the same amount. However, the difference between the simulated and measured cooling energy consumption is larger than the difference between the simulated and measured heating energy consumption. Therefore, the differences between the simulated and the measured values are not entirely due to the airflow rate.

When the assumed cold deck temperature is lower than the real value, the cooling energy difference is larger than the heating energy difference since the cooling coil must meet additional latent load, which does not require a corresponding increase in load on the heating coil. Based on this observation, it is concluded that the actual cold deck discharge air temperature is lower than the set-point due to malfunctioning control components or temperature sensors.

Consequently, the simulated pre-cooling deck discharge air temperature and cold deck discharge air temperature are adjusted to match the simulated and measured cooling and heating energy consumption values. It is found that the simulated cooling and heating consumption matches measured values within 5% when both the pre-cooling deck and main cold deck discharge air temperatures are assumed to be 52°F, and the hot deck air temperature is assumed to be 5°F higher than the set-point. Table 4-2 summarizes the intended or design values and the adjusted deck set-points.

Table 4-2: Summary of the Model Calibration Parameter Adjustment

Item	Schedule (EMCS)	Schedule (Adjusted)
Pre-cold deck temp. °F	60.0°F	52.0°F
Main-cold deck temp. °F	55.0°F	52.0°F

Hot deck temp. °F	If T_o<80 then
	Min(90, 85-0.25*(T_o-75))
	Else
	80
		If T_o<80 then
		Min(95, 90-0.25*(T_o-75))
		Else
		85

Figure 4-4 compares the measured and simulated heating and cooling energy consumption under adjusted control set points.

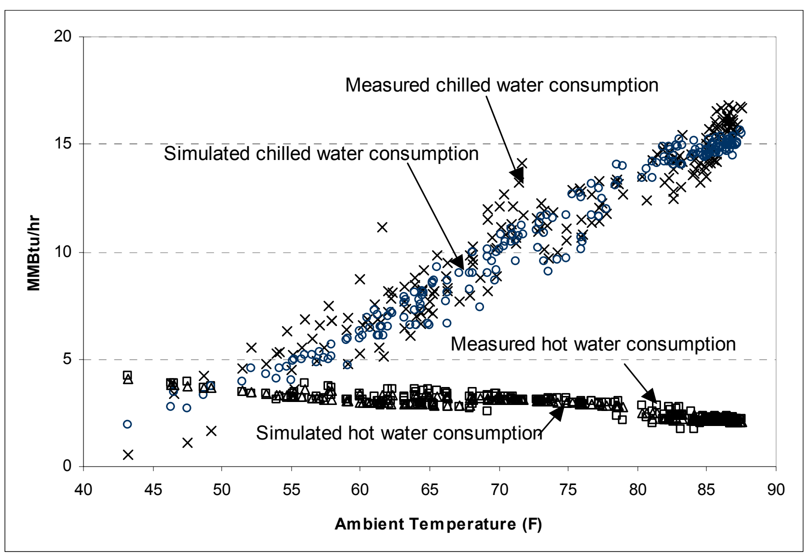

Figure 4-4: Comparison of Simulated and Measured Average Daily Heating and Cooling Energy Consumption Versus the Daily Ambient Temperature

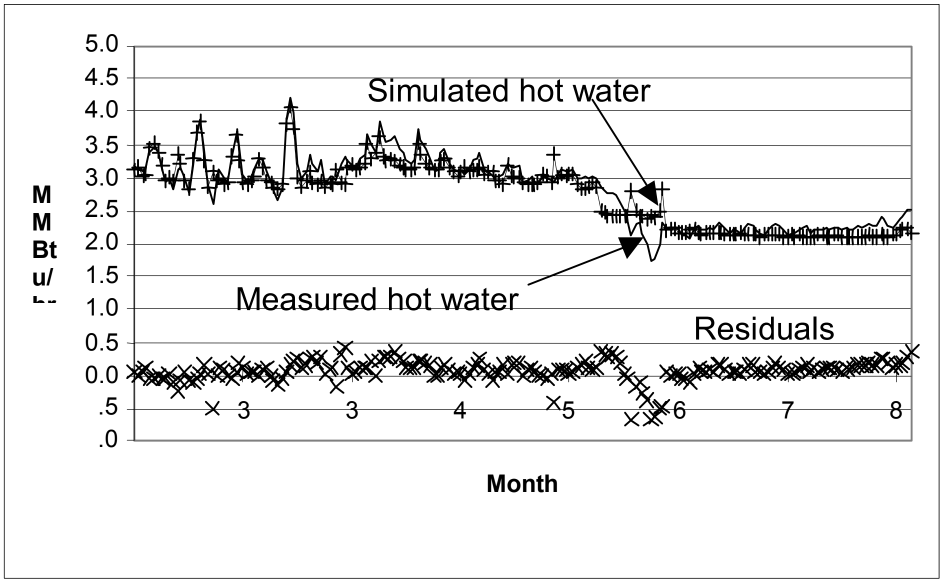

Figure 4-5: Comparison of Measured Heating Energy Consumption and Simulated

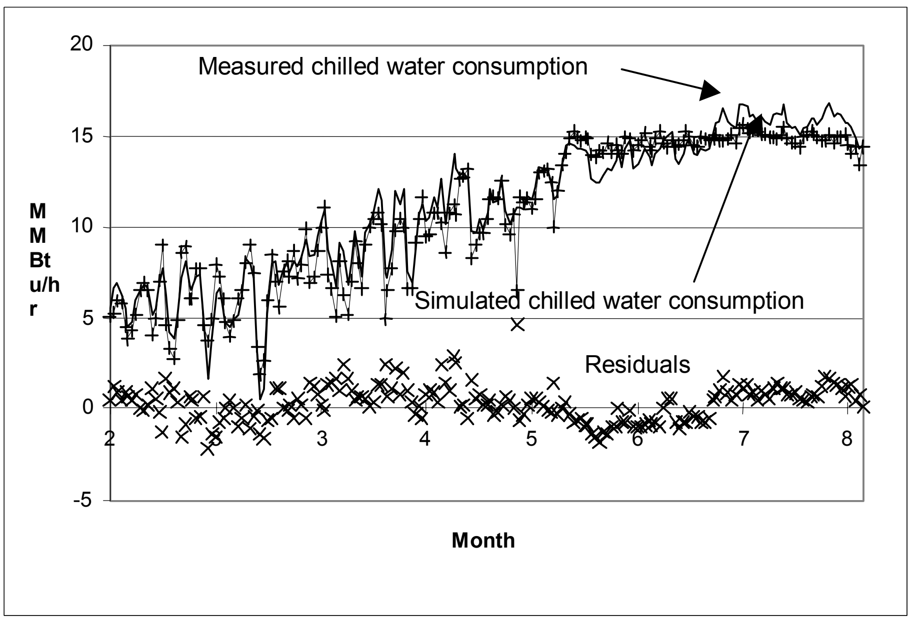

Figure 4-6: Comparison of Measured Cooling Energy Consumption and Simulated Cooling Energy Consumption with Adjusted Control Set-points

Field Verification

The hot and cold deck discharge air temperatures of all four AHUs were simultaneously measured using portable thermometers and the BAS. Table 4-3 summarizes the results.

Table 4-3: Comparison of Site Measured Deck Discharge Air Temperatures With Those Measured by BAS and Set Points

	Pre-cooling deck	Cold deck	Hot deck
Model Identified	52.0°F	52.0°F	85.0°F
Site Measured	52.8°F	51.5°F	85.0°F
BAS Measured	56.0°F	53.9°F	85.9°F
BAS Set Point	60.0°F	55.0°F	80.0°F

It was found that the model identified cold and hot deck temperatures that agree with the actual values within 0.5°F and hence had detected significant errors in the BAS measurements.
The low pre-cooling deck temperature was due to the control valve not being able to control the water flow under excessive pressure. The low cold deck and high hot deck temperatures were due to inappropriate temperature sensors, which are located directly down stream of the coils. The sensors were only 10 inches long and penetrated through a wall into the ductwork so they did not measure the average air temperature. Normally, an averaging sensor that samples the entire cross-sectional area is required to measure the coil leaving air temperature accurately.

Operational Optimization

The goal of optimizing the operating and control schedules is to minimize energy consumption while maintaining indoor comfort without expensive changes in the systems. In order to maintain indoor comfort in this building, the following conditions are required: 1) the hot deck supply air temperature should not be lower than 75 °F (23.8C) during hot summer days; and 2) the room relative humidity should be within the range of 30% to 60%.

AirModel can identify the optimal deck reset schedule automatically. It predicts the base energy consumption first under a given weather condition. Then, the operating conditions, such as cold deck and hot deck settings, are adjusted to reduce the cooling and heating energy consumption. If these parameter adjustments result in reduced energy consumption, while maintaining suitable room comfort and mechanical operation, the adjustment of parameters is continued following the same trend with reasonable step-size. This process is continued until the operating settings, which produce the minimum energy consumption, are identified.

Table 4-4 lists the operating schedules as specified by the designer, as operated in the base-case, and as optimized. The optimized operating schedules applied outside air reset in a way that decouples dehumidification and sensible cooling. The pre-cooling deck temperature is set as low as 52°F (11.1°C) so that it dries the outside air sufficiently so that the main cold deck discharge air temperature can be set based on the sensible cooling load.

Table 4-4: Comparison of Operating Schedules

Item	Design	Base-case	Optimized
O. A. treatment coil	If T_O>60 °F then 60 °F, else Off	If T_O>60 °F then 52.8 °F, else off	if T_O>60 °F then Min(54, 54-0.05*(T_O-60)) else off
Main cold deck	55 °F	51.5 °F	Min(59, 59-0.05*(T_O-50))
Hot deck	If T_O<80 then Min(90, 85-0.25*(T_O-75)) Else 85	If T_O<80 then Min(95, 90-0.25*(T_O-75)) Else 85	If T_O<80 then Min(85, 85-0.25*(T_O-60)) Else 75

Figure 4-7 compares the simulated cooling and heating energy consumption under the base-case and optimized operating schedules. The ambient air dry-bulb temperature is plotted on the horizontal axis. The cooling and heating energy consumption (in MMBtu/hr) are plotted on the vertical axis. The figure shows that the optimized schedule should reduce cooling consumption by approximately 1.0 MMBtu/hr to 2.25 MMBtu/hr with an average reduction of 1.95 MMBtu/hr and heating consumption by 0.8 MMBtu/hr to 1.25 MMBtu/hr with an average reduction of 1.13 MMBtu/hr. The simultaneous reduction of cooling and heating requirements indicates that the majority of the savings (2.26 MMBtu/hr) come from reduced reheat. The relatively higher cooling savings (0.82 MMBtu/hr greater than heating savings) indicate that the optimized schedule will remove less moisture, and increase the room relative humidity above base-case levels. It may be noted that there are sudden decreases of both the cooling and heating consumption when the ambient temperature is near 80 °F; this is due to the form of the hot deck schedule. The annual cooling savings are 17,100 MMBtu/yr, and annual heating energy savings are 9,911 MMBtu/yr. These energy savings reduce the annual energy cost by $141,100 for chilled water and $50,100 for steam. The total potential savings of $191,200/yr is 23% of the heating and cooling energy cost.

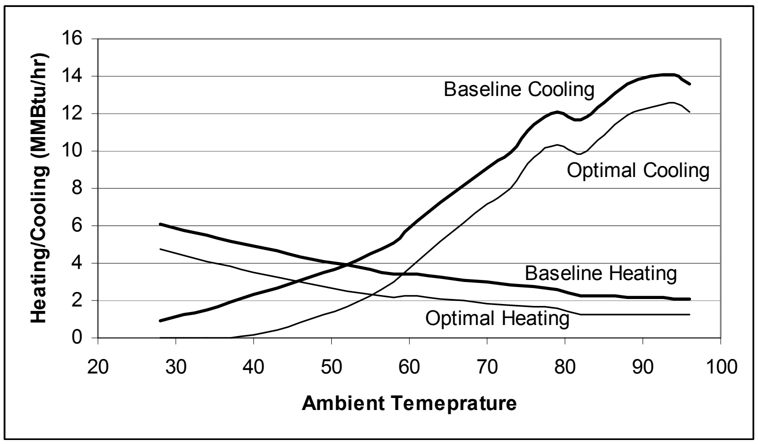

Figure 4-7: Comparison of Baseline and Optimal Heating and Cooling Energy Consumption

Figure 4-8 compares the simulated room relative humidity levels under the optimized schedule and under the base-case schedule. The predicted room relative humidity under the baes-case schedule was consistent with the BAS measured value. The optimized schedule is simulated to increase the room relative humidity to a maximum value of 57%, which is about 8% higher than the maximum value with the base-case schedule and 3% below the maximum acceptable value at this building.

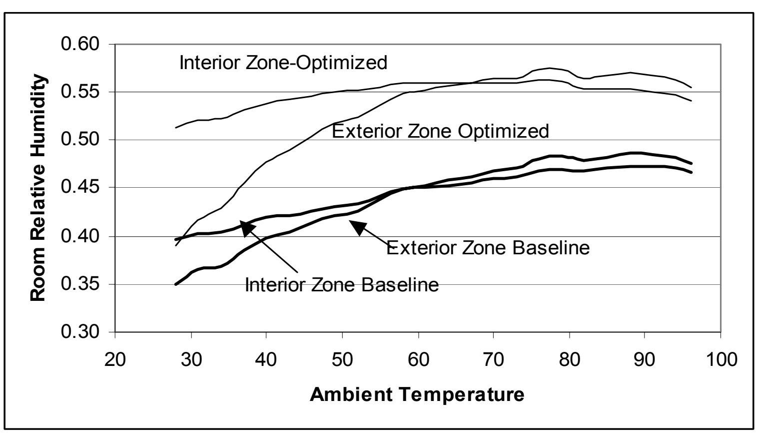

Figure 4-8: Simulated Room Relative Humidity Under Both Base-case and Optimal Operation and Control Schedules

Figure 4 -9 compares the simulated airflow rates through cold and hot air ducts under both the base-case and the optimized schedules. The base-case schedule has a cold air flow range of 130,000 CFM to 220,000 CFM and a hot air flow range of 75,000 CFM to 170,000 CFM, while the optimized schedule has a cold air flow range of 110,000 CFM to 250,000 CFM and a hot air flow rate range of 60,000 CFM to 190,000 CFM. The optimized schedule requires a larger flow range in each duct than the base-case schedule. However, this increase can be accommodated by the existing system, which has a capacity of 270,000 CFM for cold air and 220,000 CFM for hot air.

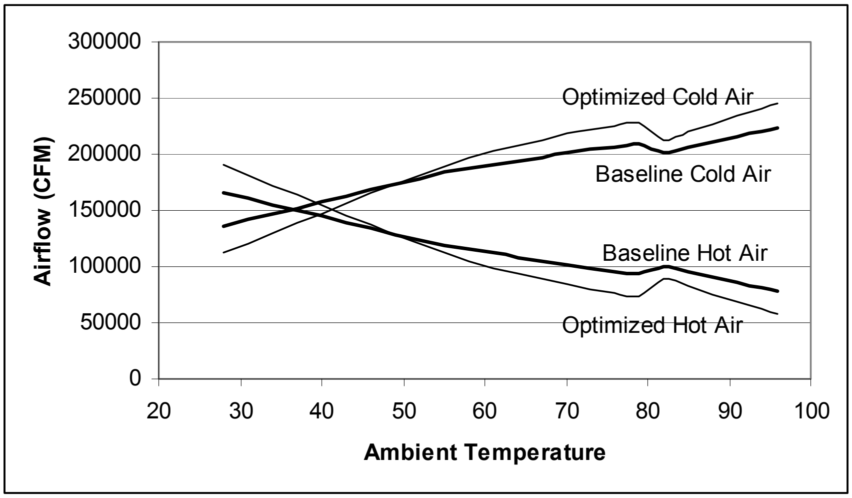

Figure 4-9: Comparison of Simulated Hot and Cold Airflow Rates Under Both Base-case and Optimal Operation Schedules

Implementation

The optimized cold and hot deck reset schedules were implemented using the BAS. The measured heating energy consumption is presented in Figure 4-10 for both the base-case and optimized periods. The measured cooling energy consumption is presented in Figure 4-11.

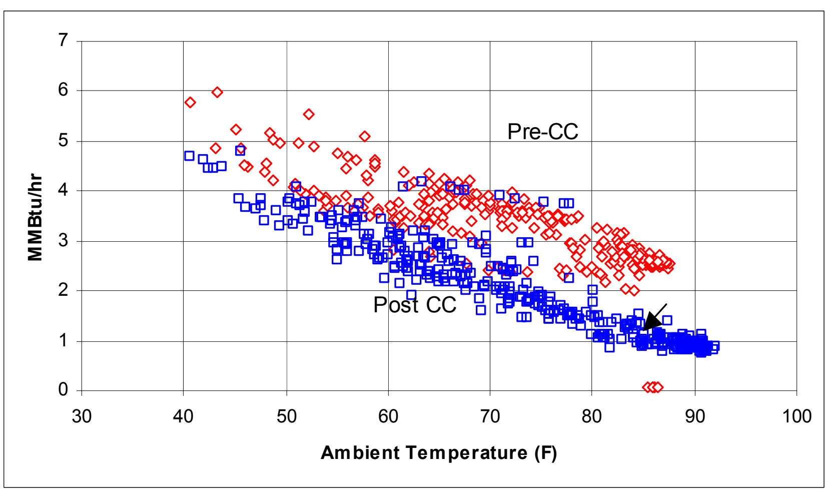

Figure 4-10: Comparison of Measured Heating Energy Consumption Under Both Base-case and Optimal Control Schedules

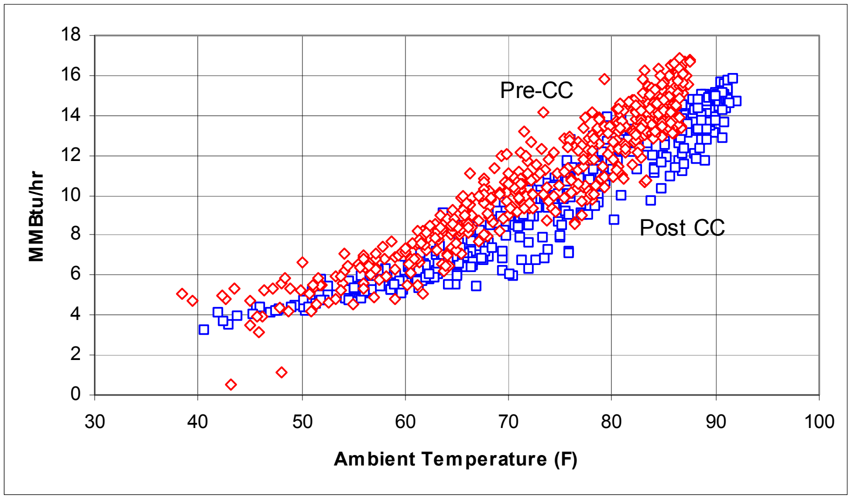

Figure 4-11: Comparison of Measured Cooling Energy Consumption Under Both Base-case and Optimal Control Schedules

The measured results show that the chilled water consumption is reduced by 1.5 MMBtu/hr to 2.5 MMBtu/hr as the ambient temperature varies from 30°F to 95°F. The heating energy consumption is reduced by 1.0 MMBtu/hr to 1.5 MMBtu/hr over the same temperature range. The results are consistent with the potential savings predicted by the calibrated models.

5. DEMONSTRATION PROJECT - SINGLE DUCT AIR HANDLING UNITS

Building and HVAC Systems

The Basic Research Building (BRB) at M. D. Anderson (MDA) Cancer Center is a seven-story building with 123,000 ft^2 gross floor area, which includes 93,000 ft^2 for the laboratory and office section, 20,000 ft^2 for a library, and 10,000 ft^2 for mechanical rooms and other purposes. The HVAC systems operate 24 hours per day.

Four single duct constant volume air handling units (AHUs) provide cooling and heating to the laboratory and office section. The design airflow rate is 150,000 cfm with 100% outside air. Figure 5-1 presents the schematic diagram of a typical AHU. The pre-heat deck set point is 55°F. If the outside air temperature is below 55°F, the pre-heat coil warms the air temperature to 55°F. If the outside air temperature is higher than 55°F, the pre-heat valve is closed. The cold deck temperature is set at 55°F. The room temperature is controlled using reheat. If the room temperature is below the set point, which varies from 72°F to 75°F from room to room, the reheat coil is turned on to maintain the room temperature.

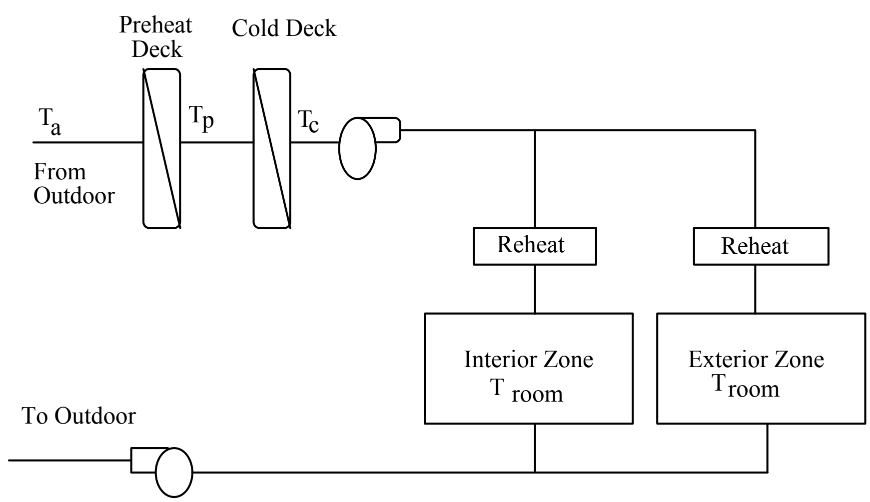

Figure 5-1: Schematic Diagram of Single Duct Air Handling Units

In addition to the single duct system that serves most of the building, there is one dual duct constant volume air handling unit, which provides cooling and heating to the library section. The design airflow is 27,000 cfm with 50% outside air intake. Figure 5-2 presents the schematic diagram of the dual duct air handling unit for the library section. The cold deck set point is 55°F. The hot deck set point varies from 85°F to 110°F as the outside air temperature decreases from 85°F to 40°F.

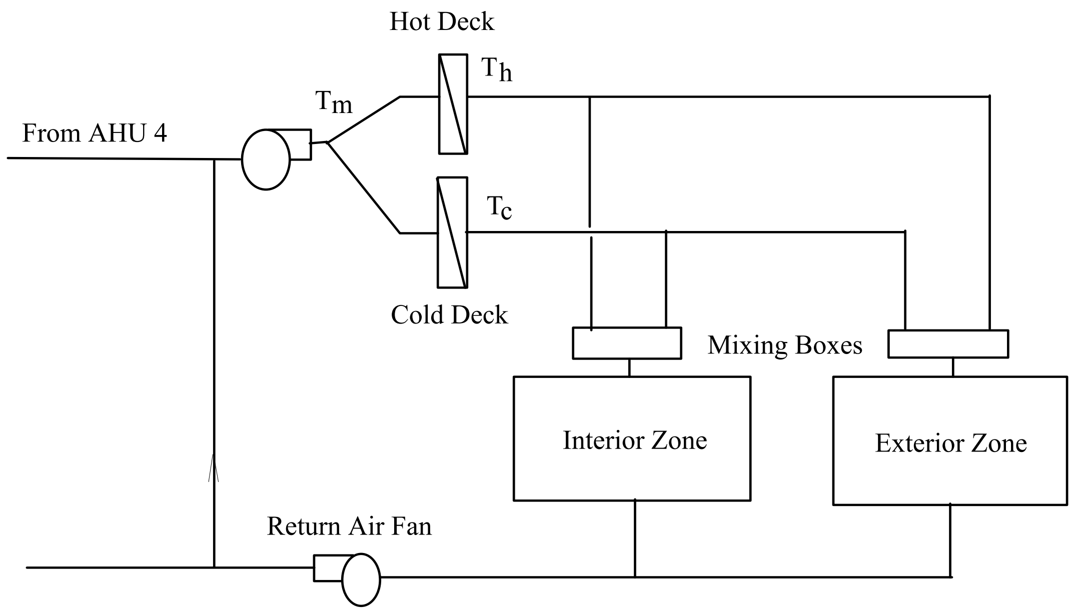

Figure 5-2: Schematic Diagram of Dual Duct Air Handling Unit for Library Section

Three single duct air handling units provide heating and cooling to mechanical rooms and other spaces. The design airflow is 14,000 cfm with 100% return air. Figure 5-3 presents the schematic diagram of these systems. The cold deck set point is 55°F. If the room temperature is satisfied, the AHUs will be turned off.

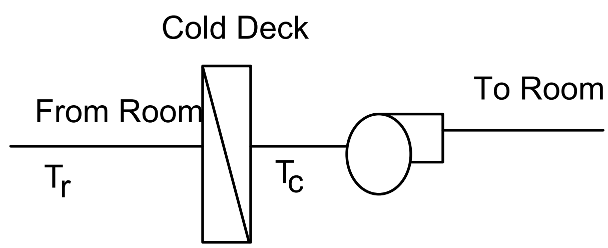

Figure 6-3: Schematic Diagram of Single Duct Air Handling Units for Mechanical Rooms

The building heating and cooling energy consumption are measured and recorded using a dedicated logger. The heating and cooling signals are split from utility meters. Figure 5-4 presents the measured hourly heating and cooling energy consumption versus the ambient temperature.

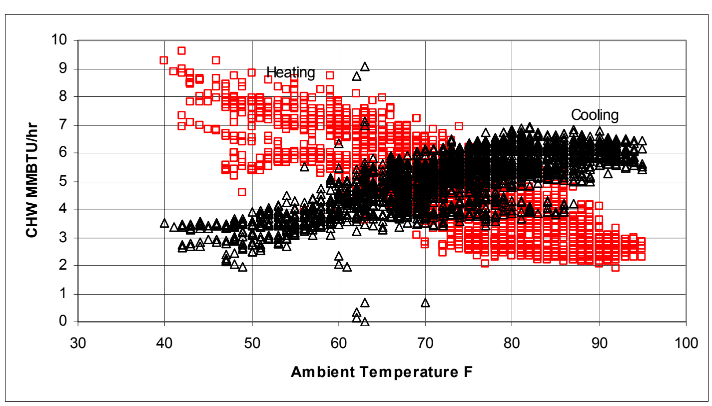

Figure 5-4: Measured Hourly Heating and Cooling Energy Consumption Versus the Ambient Temperature

Baseline Development

AirModel was used to simulate the building heating and cooling energy consumption using simplified building and system models. The building was divided into two parts: the laboratory section, which uses 100% outside air and the library section, which uses 50% outside air. Each part was simplified to two zones: interior and exterior. The design operational schedules were used in the simulation.

Figure 5-5 compares the measured heating and cooling with baseline heating and cooling energy consumption. The baseline energy consumption was simulated using actual Houston weather but not the weather data corresponding to the measured energy consumption, since the measured dew point temperature was missing for the measured energy consumption period. The baseline heating is significantly less than the measured heating while the baseline cooling is significantly higher than the measured cooling.

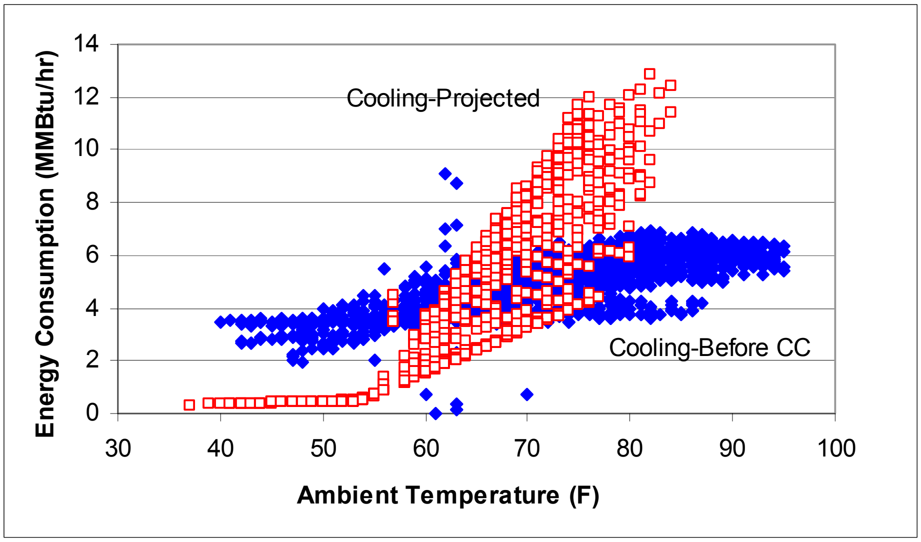

Figure 5-5a: Comparison of Baseline and Measured Cooling Energy Consumption

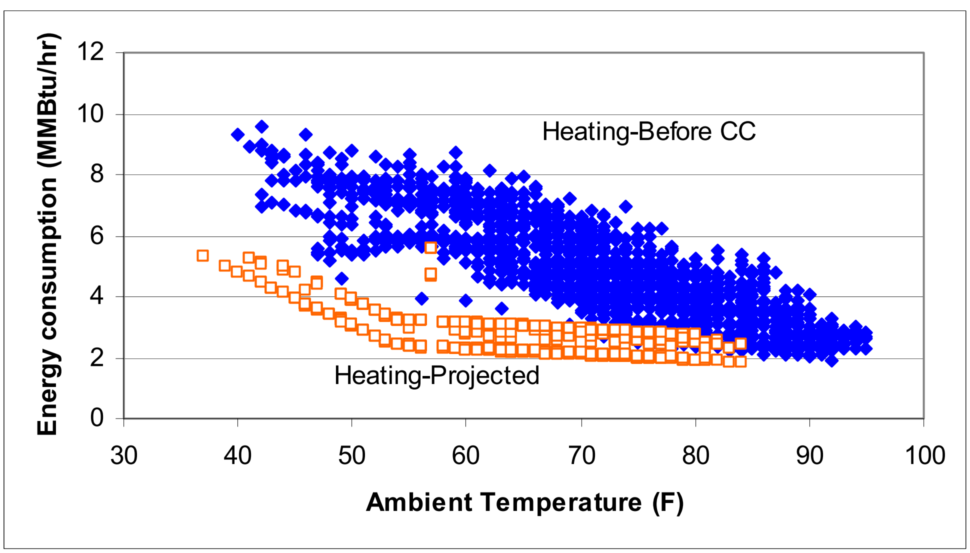

Figure 5-5a: Comparison of Baseline and Measured Cooling Energy Consumption

Fault Detection and Diagnosis

The baseline cooling is approximately twice as high as the measured values during the peak summer period while the baseline heating is slightly lower than the measured values during winter. This indicates that a fault may exist in the cooling energy metering system. Since the measured value is approximately 50% of the baseline, it was suggested that the scaling factor or the engineering conversion was set incorrectly. The measured cooling energy consumption is adjusted by a factor of 2. Figure 5-6 presents the corrected heating and cooling energy consumption.

Later, field inspection found that the by-pass line for the utility meter was fully open. Consequently, the utility meter only measured half of the chilled water flow.

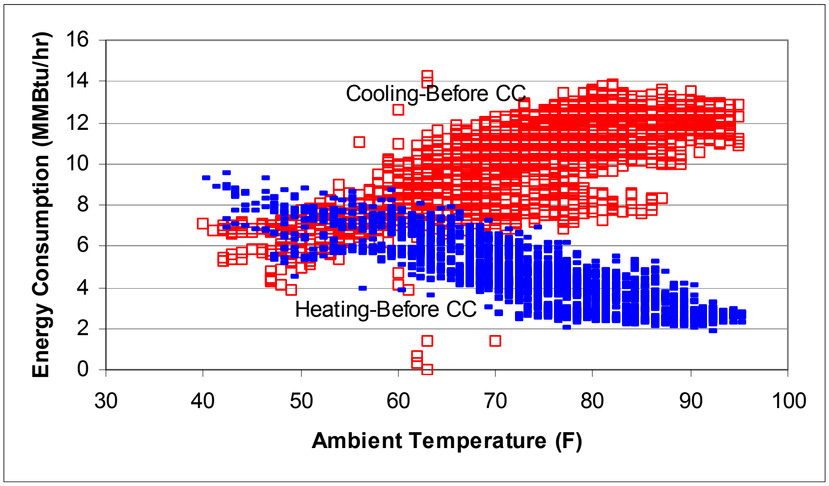

Figure 5-6: Measured Heating and Cooling Energy Consumption After Meter Correction

The difference between the measured and simulated cooling energy consumption decreases as the ambient temperature increases from 55°F to 95°F. The difference decreases when the ambient temperature decreases from 55°F to 30°F. This indicates a leaking chilled water valve. The leaking chilled water valve over-cooled the air. The terminal reheat-coils reheated the air to maintain room temperature, causing significant waste of heating and cooling energy.

Leaking chilled water flow can arise for a number of reasons. A recommendation was given to inspect the control valves.

Field Inspection

A field inspection was conducted and found that: (1) all control valves were less than 3 months old; (2) existing pneumatic lines were used when the valves were replaced; (3) all chilled water valves are normally open with a range of 3 to 8 psig; and (4) the maximum control pressure to the valves was 5 psig due to old, leaking pneumatic lines. As a result, it was not possible to close the valves fully.

This confirmed that the leaking chilled water control valves were the primary cause of the poor performance. Fixing the leaking pneumatic lines was expected to reduce the heating and cooling energy consumption to the baseline level.

Operational Optimization

It was suggested to reset the supply air temperature from 57°F to 59°F as the outside air temperature decreases 100°F to 59°F. This will decrease simultaneous heating and cooling significantly with a moderate room humidity level increase.

Implementation

The implementation included replacing the pneumatic lines and programming the reset schedule into the BAS system. These changes were made at the same time.

Figure 5-7 compares the measured chilled water consumption before fault detection and diagnosis, the chilled water consumption after fixing the pneumatic lines and implementing the optimized schedule, and the simulated optimal consumption. Figure 5-8 provides the same comparisons for heating water.

The measured annual cooling energy savings are 28,900 MMBtu/yr, and heating energy savings are 16,162 MMBtu/yr. The total annual cost savings are $369,000/yr, which includes heating savings of $129,000 and cooling savings of $240,000.

When the ambient temperature is lower than 50°F, the measured energy consumption agrees with the simulated energy consumption. When the ambient temperature is higher than 50°F, the measured energy consumption is somewhat higher than the simulated energy consumption. It appears that the building has other problems such as leaking reheat valves and excessive airflow.

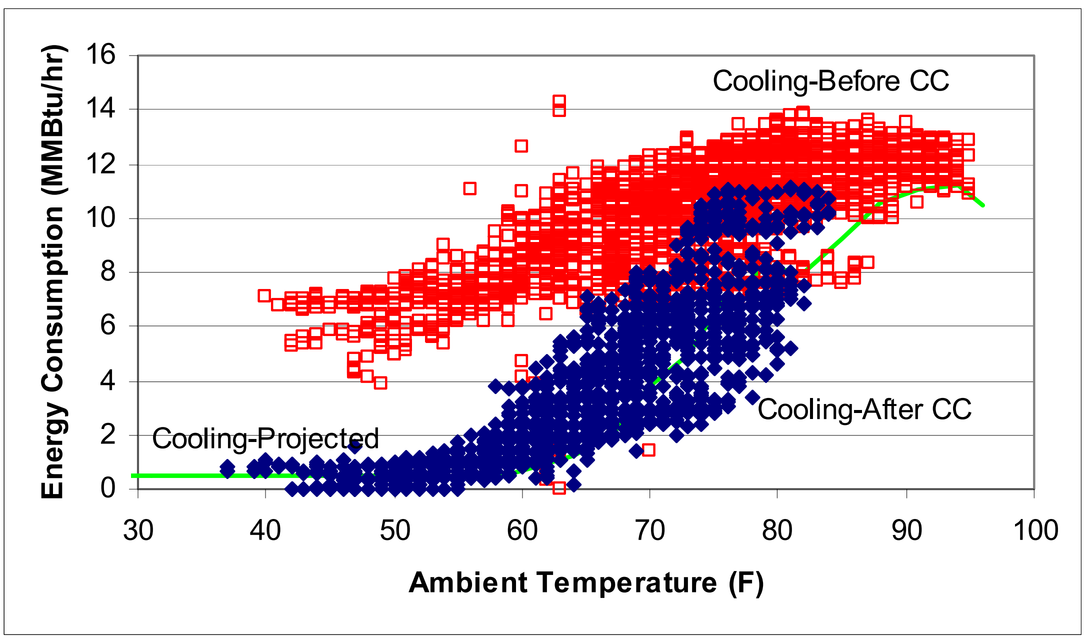

Figure 5-7: Comparison of Measured Cooling Energy Consumption Before and After Repair of Leaky Pneumatic Lines and Implementation of Optimal Reset Schedule

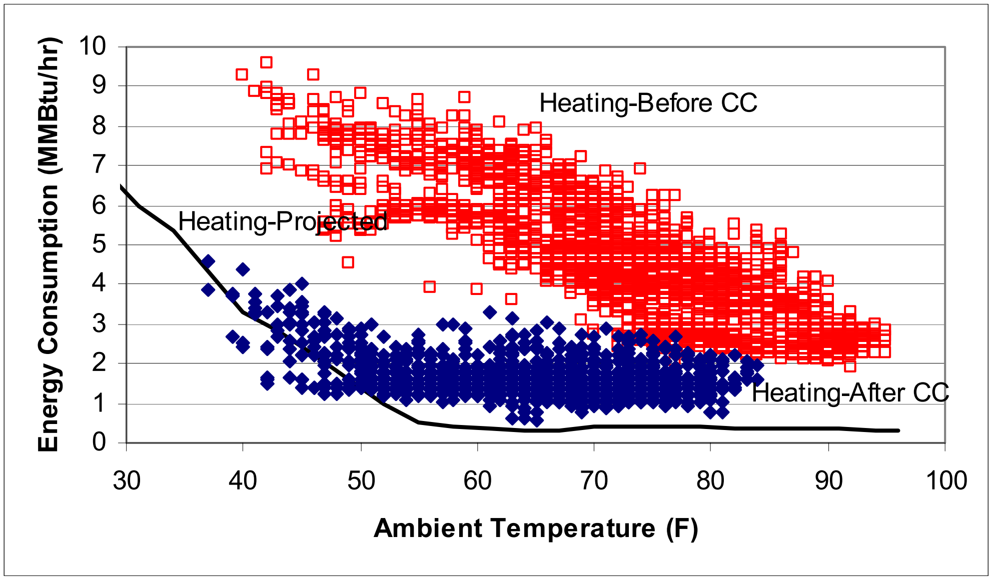

Figure 5-8: Comparison of Measured Heating Energy Consumption Before and After Repair of Leaky Pneumatic Lines and Implementation of Optimal Reset Schedule

Summary

The simulation effectively identified HVAC component problems and was used to develop optimized HVAC operation and control schedules in Case Study 1. Likewise, it identified the metering and valve leakage problems successfully in the second case. Re-heat valve leakage problems and excessive airflow problems were identified after fixing the leaking chilled water valve. This suggests that on-line fault detection should be an on-going process. The simulation indicated that building thermal energy consumption would be reduced by 23%, or $191,200/yr by using the optimized operating schedules in the building of Case Study 1. The measured energy savings were consistent with the simulated savings.

These results, coupled with similar experience in other buildings strongly support the potential value of on-line simulation as a diagnostic and optimization tool for building operation.

6. ASSESSMENT OF ONLINE SIMULATION FOR FAULT DETECTION AND DIAGNOSIS

Assessments were conducted for both AirModel and EnergyPlus. Since EnergyPlus has a more powerful simulation engine, it should have at least as much potential for use in online simulation as AirModel, providing it is equipped with proper interfaces. Therefore, two demonstration case studies were performed using AirModel for fault detection and diagnosis. One case involved a building with dual duct AHUs and the other a building with single duct AHUs.

General Assessment of AirModel

Since 1993, engineers from the Energy Systems Laboratories at Texas A&M University and the University of Nebraska, have been using AirModel for: (1) detection of energy inefficient operation; (2) diagnosis of inefficient operational schedules and major system faults, (3) development of improved operational schedules, (4) prediction of commissioning energy savings, and (5) as a baseline model for measurement of energy savings. Several papers have been published that discuss case studies and guidelines for use in these applications [Liu et al. 1994, Liu et al., 1995, Liu and Claridge 1995, Liu et al., 1997, Liu and Claridge, 1998, Wei et al. 1998, Giebler et al. 1998, Liu et al. 1998, Wei et al. 2000].

The experience documented in the case studies in the section to follow as well as others noted above indicates that Airmodel can detect energy problems that cause an approximate 5% increase in overall heating and/or cooling consumption. It can also be used to assist engineers in quickly diagnosing the actual mechanical and control system problems as illustrated in the case studies to follow.

AirModel can be used for on-line simulation through two approaches: parallel simulation or integrated simulation. For parallel simulation, AirModel will be installed in the central control system computer. AirModel will then be calibrated to represent the existing facility; an optimal control strategy is then developed and implemented in the calibrated model . The BAS system reports the key measured parameters, such as outside air temperature and relative humidity, heating energy, cooling energy, fan power, airflow rate, and room conditions. AirModel will simulate energy consumption and indoor conditions using the optimized calibrated inputs with BAS reported weather conditions. The measured and simulated energy consumption and indoor conditions will then be compared, and significant differences will be reported to the facility engineers or operators. Use of parallel simulation in the off-line mode (e.g. case studies referenced above) has resulted in approximately 20% reduction in energy use when compared with normal operating practices.

Due to its simplicity, AirModel could also be embedded in the BAS system. Modules of AirModel would receive the measured variables and simulate the energy consumption and room conditions. The comparison of measured data and simulated results could be performed in real time. This ‘integrated’ approach is best suited to individual system fault detection and diagnosis.

AirModel does have some deficiences for use in online simulation. It is robust in airside simulation but is less robust in waterside simulation and fault detection. Waterside modeling should be improved XX. It also uses simplified building load models generally making it unsuitable for detecting dynamic HVAC system or control problems.XX

General Assessment of EnergyPlus

EnergyPlus has essentially all the modeling capabilities of AirModel and hence should do the same job as AirModel for off-line fault detection if it is used properly. Currently, use of EnergyPlus requires more effort than AirModel, even for the same number of zones. This is due to lack of a suitable interface. However, this issue is now being addressed by third party software developers. It is expected that use of EnergyPlus for on-line simulation can potentially decrease building energy consumption by ~20% if the parallel procedure, mentioned above, is followed.

EnergyPlus may do a better job of dynamic fault detection and individual system fault detection since it uses dynamic load modeling. EnergyPlus also allows the user to specify output parameters.

EnergyPlus also has some deficiencies for use in online simulation. It is an energy balance based simulation program and does not simulate loop mechanical parameters, such as pressure loss. Because of this limitation, it is hard to detect some faults, such as excessive fan power due to an incorrect static pressure set-point. Because of the size and complexity of EnergyPlus, it is not suitable for use with the integrated approach for present BAS systems.

7. PLANS FOR FUTURE WORK

Two phase demonstration is planned. During the first phase, one or two commercial buildings will be selected. The building energy consumption and weather data will be measured in real time. AirModel will be run in parallel to the building operation. An interface will be developed to integrate the building automation system and AirModel input and output. Faults will be identified using discrepancies between the measured and simulated energy consumption. A manual of simulation based functional test procedures will be developed.

During the second phase, EnergyPlus will be used to identify building level faults as conducted in the first phase by AirModel. Currently, a number of system models are not developed for EnergyPlus. The AirModel program will be used to identify the system level faults, such as AHUs, chillers, and boilers. The potential and capabilities of the simulation based functional test will be documented based on the field application. A manual of fault diagnosis procedures will be developed for use with simulation programs.

To demonstrate the potential of simulation for fault detection, the procedures should be implemented in full scale buildings. It is planned to use the PKI Building at the University of Nebraska as the first demonstration site.

The PKI building is a 190,000 square-foot teaching and research building, located in Omaha, Nebraska. The Energy Systems Laboratory is located inside the PKI building. It was built in 1997 with a modern building automation system. It has 10 single duct variable air volume systems. The building has its own chiller and boiler plant.

The building was designed as an architectural engineering demonstration building. No ceiling tiles are installed in most portions of the building. All major mechanical and control devices can be directly observed and inspected.

During the design phase, the power distribution system was designed so that the electricity consumption can be measured for each major section and each major type. With a minimum metering investment (e.g. current transducers and pressure transducers), good quality data can be obtained to enhance the quality of fault detection.

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APPENDIX A: SIMULATION PROGRAMS

This appendix provides summary descriptions of the 15 programs listed in the table below.

		Detailed general purpose detailed whole building energy simulation programs
1	APACHE	thermal design, thermal analysis, energy simulation, dynamic simulation, system simulation
2	BLAST	energy performance, design, retrofit, research, residential and commercial buildings
3	DOE-2	energy performance, design, retrofit, research, residential and commercial buildings
4	EnergyPlus	energy simulation, load calculation, building performance, simulation, energy performance, heat balance, mass balance
5	HAP v4.0	energy performance, load calculation, energy simulation, HVAC equipment sizing
6	TRACE 700	energy performance, load calculation, HVAC equipment sizing, energy simulation, commercial buildings
7	VisualDOE	energy performance, design, retrofit, research, residential and commercial buildings
		Simplified general purpose whole building energy simulation programs
1	ASEAM	energy performance, existing buildings, commercial buildings
2	System Analyzer	energy analyses, load calculation, comparison of system and equipment alternatives
		Specialized building energy simulation programs
1	HBLC	heating and cooling loads, heat balance, energy performance, design, retrofit, residential and commercial buildings
2	HVACSIM+	HVAC equipment, systems, controls, EMCS, complex systems
3	SPARK	object-oriented, research, complex systems, energy performance
4	TRNSYS	design, retrofit, research, energy performance, complex systems, commercial buildings
		Data visualization/analysis programs
1	ENFORMA	data acquisition, energy performance, building diagnostics, HVAC systems, lighting systems
2	Visualize-IT Energy Information and Analysis Tool	energy analysis, rate comparison, load profiles, interval data

The information provided in this appendix is taken from the DOE web page for all programs described. AirModel is not shown on the DOE web page, so the program description is given only in the main text. This information can be found at: http://www.eren.doe.gov/buildings/tools_directory/database

ASEAM

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Evaluation of high-potential, cost effective energy efficiency projects in existing Federal buildings; calculates results that are within 4-5% of DOE-2 annual energy results; using quick input routines, permits evaluation of a 10,000 ft2 building in about ten minutes. ASEAM (A Simplified Energy Analysis Method) Version 5.0 automatically creates DOE-2 input files. The FEMP Architects and Engineers Guide to Energy Conservation in Existing Buildings (published November 1990) uses ASEAM as a primary example of how software can be used in over 180 retrofit projects.

Keywords: energy performance, existing buildings, commercial buildings

Expertise Required: Designed to be used by non-engineers with minimal training.

Users: Several hundred.

Audience: Federal energy personnel.

Input: Building type and location, outside dimensions, percent glazing, usage patterns, number of floors, central systems and plant.

Output: Average monthly and annual energy savings from retrofits, taking into account all interactive effects using parametric analysis for optimization.

Computer Platform: PC-compatible, 286 minimum, with math coprocessor preferred.

Programming Language: C

Strengths: Currently allows an engineer to easily perform very sophisticated whole building energy analysis (calibrates to utility data using Lotus macros, does parametric analysis on dozens of energy conservation opportunities).

Weaknesses: Should have the same analytical process fully automated for less sophisticated users.

BLAST

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Performs hourly simulations of buildings, air handling systems, and central plant equipment in order to provide mechanical, energy and architectural engineers with accurate estimates of a building's energy needs. The zone models of BLAST (Building Loads Analysis and System Thermodynamics), which are based on the fundamental heat balance method, are the industry standard for heating and cooling load calculations. BLAST output may be utilized in conjunction with the LCCID (Life Cycle Cost in Design) program to perform an economic analysis of the building/system/plant design.

Keywords: energy performance, design, retrofit, research, residential and commercial buildings

Expertise Required: High level of computer literacy not required; engineering background helpful for analysis of air handling systems.

Users: Over 500.

Audience: Mechanical, energy, and architectural engineers working for architect/engineer firms, consulting firms, utilities, federal agencies, research universities, and research laboratories.

Input: Building geometry, thermal characteristics, internal loads and schedules, heating and cooling equipment and system characteristics. Readable, structured input file may be generated by HBLC (Windows) or the BTEXT program.

Output: More than 50 user-selected, formatted reports printed directly by BLAST; also the REPORT WRITER program can generate tables or spreadsheet-ready files for over one hundred BLAST variables.

Computer Platform: PC-compatible, 386 or higher; HP/Apollo. Source code is available and has been successfully compiled on most UNIX workstations.

Programming Language: FORTRAN

Strengths: PC Format has Windows interface as well as structured text interface; detailed heat balance algorithms allow for analysis of thermal comfort, passive solar structures, high and low intensity radiant heat, moisture, and variable heat transfer coefficients -- none of which can be analyzed in programs with less rigorous zone models.

Weaknesses: High level of expertise required to develop custom system and plant models.

DOE-2

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Hourly, whole-building energy analysis program calculating energy performance and life-cycle cost of operation. Can be used to analyze energy efficiency of given designs or efficiency of new technologies. Other uses include utility demand-side management and rebate programs, development and implementation of energy efficiency standards and compliance certification, and training new corps of energy-efficiency conscious building professionals in architecture and engineering schools.

Keywords: energy performance, design, retrofit, research, residential and commercial buildings

Expertise Required: Recommend 3 days of formal training in basic and advanced DOE-2 use.

Users: 800 user organizations in U.S., 200 user organizations internationally; user organizations consist of 1 to 20 or more individuals.

Audience: Architects, engineers in private A-E firms, energy consultants, building technology researchers, utility companies, state and federal agencies, university schools of architecture and engineering.

Input: Hourly weather file plus Building Description Language input describing geographic location and building orientation, building materials and envelope components (walls, windows, shading surfaces, etc.), operating schedules, HVAC equipment and controls, utility rate schedule, building component costs. Available with a range of user interfaces, from text-based to interactive/graphical windows-based environments.

Output: 20 user-selectable input verification reports; 50 user-selectable monthly/annual summary reports; user-configurable hourly reports of 700 different building energy variables.

Computer Platform: PC-compatible; Sun; DEC-VAX; DECstation; IBM RS 6000; NeXT; 4 megabytes of RAM; math coprocessor; compatible with Windows, UNIX, DOS, VMS.

Programming Language: FORTRAN 77

Strengths: Detailed, hourly, whole-building energy analysis of multiple zones in buildings of complex design; widely recognized as the industry standard.

Weaknesses: High level of user knowledge.

EnergyPlus

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

A new generation building energy simulation program that builds on the most popular features and capabilities of BLAST and DOE-2. EnergyPlus will include innovative simulation capabilities including time steps of less than an hour, modular systems simulation modules that are integrated with a heat balance-based zone simulation, and input and output data structures tailored to facilitate third party interface development. Other planned simulation capabilities include solar thermal, multizone air flow, and electric power simulation including photovoltaic systems and fuel cells.

Keywords: energy simulation, load calculation, building performance, simulation, energy performance, heat balance, mass balance

Expertise Required: High level of computer literacy not required; engineering background helpful for analysis portions.

Users: Over 500.

Audience: Mechanical, energy, and architectural engineers working for architect/engineer firms, consulting firms, utilities, federal agencies, research universities, and research laboratories.

Input: Basic EnergyPlus program (current release is Beta 4 of 5 betas) will have a simple ASCII input file. It is envisioned that private developers will wish to develop more targeted / domain specific user interfaces.

Output: Basic EnergyPlus program will have several simple ASCII output files - readily adapted into spreadsheet form for further analysis.

Computer Platform: Emphasis on platform portability. Windows 9x/NT/2000 executable will be available. Has been successfully compiled on UNIX and Linux platforms.

Programming Language: Fortran 90

Strengths: Accurate, detailed simulation capabilities through complex modeling capabilities. Input is geared to the 'object' model way of thinking. Successful interfacing using IFC standard architectural model has been demostrated. Extensive testing (comparing to available test suites) is being done during development and results will be available.

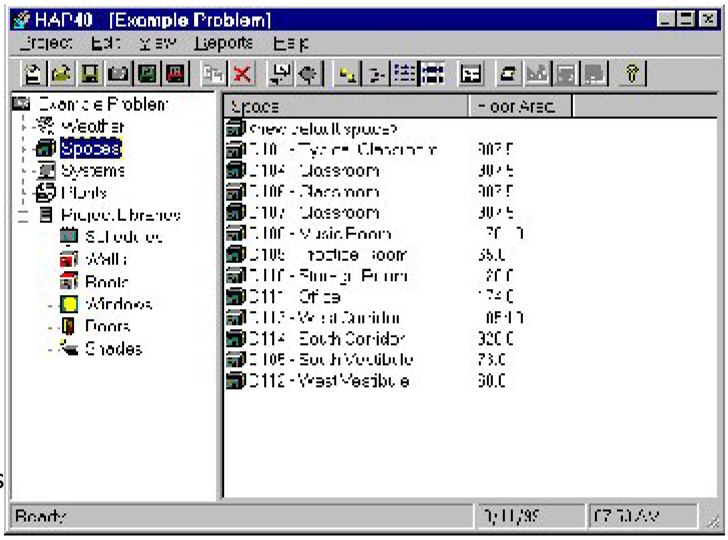
Weaknesses: Difficult to use without graphical interfaces.

Validation/Testing: EnergyPlus has been tested against the IEA BESTest building load and HVAC tests. Results are available under Testing and Validation on the

HAP V4.0

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

A versatile system design tool and a powerful energy simulation tool in one package. HAP (Hourly Analysis Program) v4.0 for Windows also provides the ease of use of a Windows-based graphical user interface, and the computing power of Windows 32-bit software.



HAP's design module uses a system-based approach which tailors sizing procedures and reports to the specific type of system being considered. Central AHUs, packaged rooftop units, split systems, fan coils and PTACs can easily be designed, as can CAV, VAV, single and multiple-zone systems. The ASHRAE-endorsed Transfer Function Method is used to calculate building heat flow.

HAP's energy simulation module performs a true 8760 hour energy simulation of building heat flow and equipment performance. It uses TMY weather data and the Transfer Function Method. Many types of air handling systems, packaged equipment, and plant equipment can be simulated. Costs can be computed using complex utility rates. Extensive, easy to read reports and graphs document hourly, daily, monthly and annual energy and cost performance.

Keywords: energy performance, load calculation, energy simulation, HVAC equipment sizing

Expertise Required: General knowledge of HVAC engineering principles.

Users: 5000 worldwide.

Audience: Practicing engineers involved in the design, specification and analysis of commercial HVAC systems/equipment. Instructional tool in colleges and universities. Design/build contractors, HVAC contractors, facility engineers and other professionals involved in the design and analysis of commercial building HVAC systems. It can be used for new design, retrofit and energy conservation work.

Input: Building geometry, envelope assemblies, internal heat gains and their schedules; equipment components, configurations, controls and efficiencies; utility rates.

Output: 48 design and analysis reports available to view or print. Design reports provide system sizing information, check figures, component loads, and building temperatures. Simulation reports provide hourly, daily, monthly and annual performance data. Users control the content and format of all graphical reports.

Computer Platform: Windows 95/98/NT compatible PC, Pentium or higher, minimum 32MB RAM, minimum 20 MB hard disk space.

Programming Language: Software is compiled. Source code is not available.

Strengths: HAP balances ease of use with technical sophistication. Technical features are comparable to DOE 2.1; comparison studies with DOE 2.1 have yielded good correlation. The Windows graphical user interface, report features, data management features, on-line help system and printed documentation combine to provide an efficient, easy to use tool.

Weaknesses: HAP is not an effective tool for the research scientist. Because it is designed for the practicing engineer, HAP does not permit modification of source code to model one-of-a-kind equipment configurations and control schemes often studied in research situations.

SPARK

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

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An object-oriented program that allows the user to quickly build models of complex physical processes by connecting equation-based calculation modules from an object library. SPARK (Simulation Problem Analysis and Research Kernel) creates an executable simulation program from this network ready to be run.

See example screen images

Keywords: object-oriented, research, complex systems, energy performance

Expertise Required: High level of computer literacy required.

Users: 50

Audience: Building technology researchers and energy consultants.

Input: Calculation modules created symbolically or selected from a library, then connected using a Graphical Editor or Network Specification Language; run-time input such as time step and parameter values.

Output: Graphical display of results for any simulation variable.

Computer Platform: Windows 95/98/NT, Sun Unix, Linux, HP

Programming Language: C, C++

Strengths: Capable of modeling complex building envelopes and building HVAC systems to any level of detail; built-in problem decomposition and reduction techniques give execution times that are 10-20 times faster than similar programs. User-selectable time step allows modeling short time-step dynamics; symbolic input of equations avoids programming; Graphical Editor simplifies model description and construction of customized networks; library of HVAC components and systems.

Weaknesses: High level of user expertise in system being modeled required.

System Analyzer

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Software package for load calculation and energy and economic comparative analysis. System Analyzer permits a quick evaluation of virtually any building, system, and equipment combination. Thus, it can be used either as a scoping tool to decide what systems may be appropriate for an initial design, or to get a general feeling of how one system/equipment combination may perform over another. If a certain combination seems especially promising, further analysis can be done by exporting inputs into TRACE 600. The possibilities are endless. And since the program is Windows-based, virtually anyone with minimal HVAC training and experience can use it.

Keywords: Energy analyses, load calculation, comparison of system and equipment alternatives

Expertise Required: Basic knowledge of HVAC equipment, systems and terms.

Users: Approximately 800 users worldwide.

Audience: Utility companies and ESCOs who wish to promote alternative cooling strategies; architects and marketing persons who may use this as a powerful, interactive presentation tool; and mechanical engineers who design, size and calculate energy consumption for HVAC systems.

Input: Building design parameters, system configurations and utility rates.

Output: Print any of the 30 design and analysis reports and graphs such as building loads, equipment energy consumption, economic analysis, yearly cash flows and monthly building load profiles for comparisons or presentations.

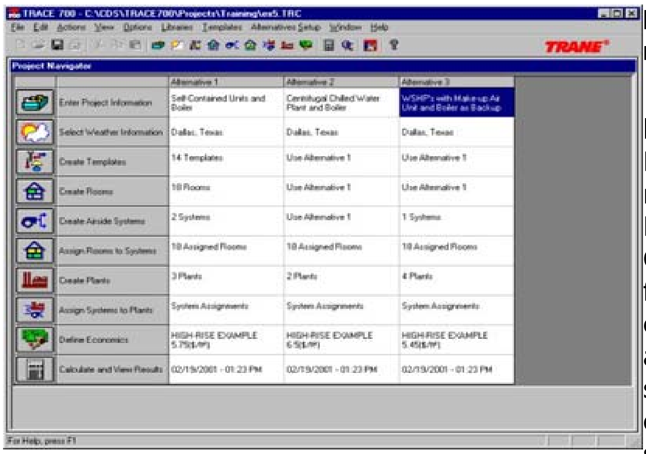
Computer Platform: PC-compatible 486 or higher (Pentium recommended), Windows 3.1 or higher, 12 MB RAM (16 MB recommended); 13 MB free hard disk space.

Programming Language: CA-Realizer

Strengths: System Analyzer is a powerful, interactive presentation tool and it's graphical interface allows even a beginner with minimal HVAC experience to get a complete energy and economic analysis in as little as 10 minutes. The graphs, when printed on a color printer, provide powerful visual proof for proposals to justify better HVAC systems.

Weaknesses: The program provides reliable comparative system analyses, but lacks some of the extensive details of load and energy components available in the TRACE suite.

TRACE 700



Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Trane's **TRACE™ 700** software - the latest version of Trane Air Conditioning Economics - brings the algorithms recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) to the familiar Microsoft® Windows® operating environment. Use it to assess the energy and economic impacts of building-related selections such as architectural features, comfort-system design, HVAC equipment selections, operating schedules, and financial options.

Flexible data entry, coupled with multiple views and "drag-and-drop" load assignments, simplify the modeling process and help you identify optimal zoning and plant configurations. Compare up to four alternatives for a single project by modeling various air distribution and mechanical system/control options; then assess the life-cycle cost and payback of each combination based on 8,760 hours of operation... without investing lots of extra time.

Templates provide a fast, easy way to analyze the effects of changes in building loads such as airflows, thermostat settings, occupancy, and construction. An extensive library of construction materials, equipment, and weather profiles (nearly 500 locations) enhances the speed and accuracy of your analyses. Choose from seven different ASHRAE cooling and heating methodologies, including the Exact Transfer Function.

See example screen images

Keywords: Energy performance, load calculation, HVAC equipment sizing, energy simulation, commercial buildings

Expertise Required: General knowledge of HVAC engineering principles, building geometry, and the Microsoft Windows operating system

Users: Approximately 1,200 worldwide, including single and site/LAN licenses

Audience: Engineers, architects, and contractors who design and analyze commercial HVAC systems/equipment for new and existing buildings; also energy consultants and utility companies; building technology researchers; state and federal agencies; colleges and universities

Input: Building design parameters; operating schedules; HVAC system configurations, equipment types, and control strategies; utility rates

Output: Display, print, graph, or export any of 54 monthly/yearly summary reports and hourly analyses, including system "checksums," psychrometric state points, peak cooling/heating loads, building envelope loads, building temperature profiles, equipment energy consumption, and ASHRAE 90 analysis

Computer Platform: Personal computer with a Pentium® 233 or higher processor, Microsoft Windows 95/98/2000/ME/NT operating system, 128 megabytes (MB) of RAM, 80 MB of free hard disk space, Super VGA display, CD-ROM drive, and a Microsoft-compatible pointing device

Programming Language: Microsoft® Visual C++ development system

Strengths: Models 30 different airside systems, plus many HVAC plant configurations and control strategies, including thermal storage, cogeneration, and fan-pressure optimization. Customizable libraries and templates simplify data entry and allow greater modeling accuracy. Documentation includes detailed online Help and a printed modeling guide. Experienced HVAC engineers and support specialists provide free technical support.

Weaknesses: Formal training is recommended for new users (Visit our Web site for training options.)

TRNSYS

Description below taken from
http://www.eren.doe.gov/buildings/tools_directory/database

Modular system simulation software; includes many of the components commonly found in thermal energy systems as well as component routines to handle input of weather or other time-dependent forcing functions and output of simulation results. TRNSYS (TRaNsient SYstem Simulation Program) is typically used for HVAC analysis and sizing, solar design, building thermal performance, analysis of control schemes, etc.

Keywords: design, retrofit, research, energy performance, complex systems, commercial buildings

Expertise Required: None to use standard package; FORTRAN knowledge helpful for developing new components

Users: 1000 US; 2000 worldwide.

Audience: Engineers, researchers, architects.

Input: TRNSYS input file, including building input description, characteristics of system components and manner in which components are interconnected, and separate weather data (supplied with program). Input file can be generated by graphically connecting components.

Output: Life cycle costs; monthly summaries; annual results; histograms; plotting of desired variables (by time unit); online variable plotting (as the simulation progresses).

Computer Platform: Windows 95 and NT for TRNSYS interface programs. (Distributed source code will compile and run on any Fortran platform).

Programming Language: FORTRAN (although unnecessary for the use of standard components).

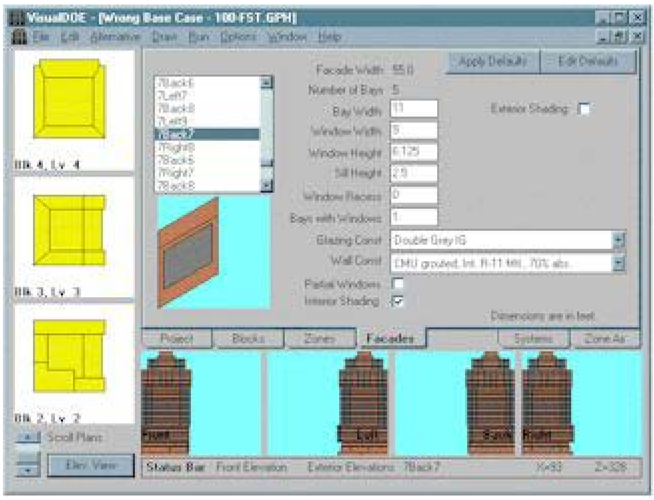
Strengths: Due to its modular approach, extremely flexible for modeling a variety of thermal systems in differing levels of complexity; supplied source code and documentation provide an easy method for users to modify or add components not in the standard library; extensive documentation on component routines, including explanation, background, typical uses and governing equations; supplied time step, starting and stopping times allowing choice of modeling periods. Version 14.2 moves all the TRNSYS utility programs to the MS Windows platform (95/NT), including a choice of graphical drag-and-drop programs for creating input files, a utility for easily creating a building input file, and a program for building TRNSYS-based applications for distribution to non-users. Web-based library of additional components and frequent downloadable updates are also available to users.

Weaknesses: No assumptions about the building or system are made (although default information is available) so the user must have detailed information about the building and system and enter this information into the TRNSYS interface.

VisualDOE

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Windows interface to the DOE-2.1E energy simulation program. Through the graphical interface, users construct a model of the building's geometry using standard block shapes or using a built-in drawing tool. Building systems are defined through a point-and-click interface. A library of constructions, systems and operating schedules is included, and the user can add custom elements as well. If desired, the program assigns default values for parameters based on the vintage and size of the building.



VisualDOE is especially useful for studies of envelope and HVAC design alternatives. Up to 20 alternatives can be defined for a single project. Summary reports and graphs may be printed directly from the program. Hourly reports of building parameters may also be viewed.

Keywords: energy performance, design, retrofit, research, residential and commercial buildings

Expertise Required: Basic experience with Windows programs is important. Familiarity with building systems is desirable but not absolutely necessary. One to two days of training is also desirable but not necessary for those familiar with building modeling.

Users: 300+, US and international.

Audience: Building designers (new and retrofit), researchers, equipment and utility marketers.

Input: Assigns default values to many of the inputs based on the building vintage and size. Required inputs include floorplan, occupancy type, and location. These are all that is required to run a simulation. Typically, however, inputs include wall, roof and floor constructions; window area and type; HVAC system type and parameters; and lighting and office equipment power.

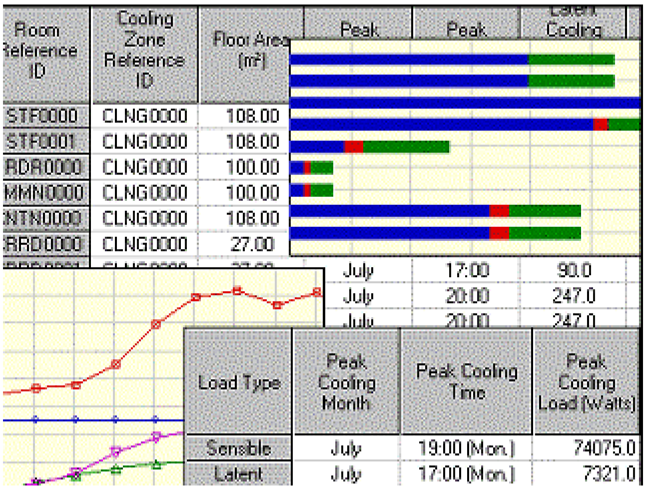
Output: Produces input and output summary reports that may be viewed on-screen or printed. A number of graphs may be viewed and printed. These graphs can compare selected alternatives and/or selected hourly variables. Standard DOE-2.1E reports may be selected.

Computer Platform: Windows 3.1, Windows 95, or Windows NT. 486 or better, 8MB+ RAM, 30MB hard drive space.

Programming Language: Visual Basic and Visual C++

Strengths: Allows rapid development of energy simulations, dramatically reducing the time required to build a DOE-2 model. Specifying the building geometry is much faster than other comparable software, making VisualDOE useful for schematic design studies of the building envelope or HVAC systems. Uses DOE-2 as the simulation engine--an industry standard that has been shown to be accurate; implements DOE-2's daylighting calculations; allows input in SI or IP units; imports CADD data to define thermal zones. For advanced users, allows editing of equipment performance curves. Displays a 3D image of the model to help verify accuracy. Allows simple management of up to 20 design alternatives. Experienced DOE-2 users can use VisualDOE to create input files, modify them, and run them from within the program.

Weaknesses: Passive solar models may not be too accurate. Natural ventilation modeling is limited to a specified air changes per hour (ACH) that may be scheduled on or off. Underground buildings must be modeled with exterior walls, although custom constructions can be entered to represent the mass of the earth. Underfloor air distribution systems may provide benefits that are not directly modeled in DOE-2. For instance, DOE-2 does not account for thermal stratification in a space. Version 2.5 of VisualDOE does not support modeling of skylights.



APACHE

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Software tool for thermal design & energy simulation related to buildings. In design mode, APACHE covers the calculation of heating, cooling and latent room loads, the sizing of room units, internal comfort analysis and codes/standards checks. In simulation mode, APACHE performs a dynamic thermal simulation using hourly weather data. Linked modules deal with the performance of HVAC plant and natural ventilation. APACHE is a component of the IES Virtual Environment, an integrated computing environment encompassing a wide range of tasks in building design.

Applications:

- Thermal design (heating, cooling & latent load calculations)
- Equipment sizing
- Codes & standards checks
- Dynamic building thermal performance analysis
- Systems and controls performance
- Energy use

Modules:

- Geometrical modelling, building data input & visualisation
- Management of data relating to materials, occupancy, plant operation and climate.
- Shading analysis
- Heat Gain calculations
- Heat Loss calculations
- Dynamic thermal simulation
- Natural ventilation & indoor air quality analysis
- HVAC system simulation
- Results presentation & analysis

Keywords: thermal design, thernal analysis, energy simulation, dynamic simulation, system simulation

Expertise Required: 2 days training is recommended for the basic modules, with additional courses available for specific applications. Available in UK and other countries by arrangement.

Users: Many throughout Europe.

Audience: mechanical building services engineers, local government, building managers & landlords, building design consultants, architects, and university research and teaching departments.

Input: Geometrical building data may be imported from a range of CAD systems via customised links or DXF files. Geometrical models may alternatively be entered using facilities within the Virtual Environment. Input of data relating to materials, occupancy, internal gains, climate, air movement and systems is managed via graphical interfaces and supported by extensive databases.

Output: APACHE presents a wide range of outputs in tabular and graphical form. Outputs may be exported in a variety of common formats.

Computer Platform: PC running Windows 95, 98 or NT (3.51 or higher). 100 MB Ram or paging disk. 100 MB disk space. CD-Rom drive.

Programming Language: Visual Basic, C++, Fortran 77

Strengths: Operates within an integrated computing environment covering a range of building analysis functions. Strong links with CAD. Undergoing rapid development, with continuing input from research and engineering practice. Supported by in-house expertise. Rigorous analysis and visualisation of shading and solar penetration. Flexible & versatile system HVAC and controls modelling. Integrated simulation of building and HVAC systems.

Weaknesses: Certain energy systems not covered currently, eg phase-change materials, roof ponds.

HBLC

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Powerful software tool for calculating heating and cooling loads for buildings. Allows the user to access complex heat-balance algorithms using a Windows interface. Geometric inputs are entered graphically using intuitive click-and-drag mouse functions and allows the user to visualize the building model as it is developed. HBLC (Heat Balance Loads Calculator) creates an input file for and runs the BLAST (Building Loads Analysis and System Thermodynamics) simulation program. After simulating, HBLC retrieves results from the simulation and can present these results in a graphical presentation. On-line helps provide valuable on-the-spot assistance that will benefit both new and experienced users. HBLC is an excellent tool which will make the process of developing BLAST input files more intuitive and efficient.

Keywords: heating and cooling loads, heat balance, energy performance, design, retrofit, residential and commercial buildings

Expertise Required: High level of computer literacy not required; engineering background helpful for analysis portions.

Users: Over 500.

Audience: Mechanical, energy, and architectural engineers working for architect/engineer firms, consulting firms, utilities, federal agencies, research universities, and research laboratories.

Input: Interactive program in Windows environment.

Output: Can access most of BLAST's features. Presents graphs, for example, individual zone loads, load splits, etc.

Computer Platform: Windows 95 or NT preferred – may be able to use Windows 3.1 environment.

Programming Language: Visual Basic

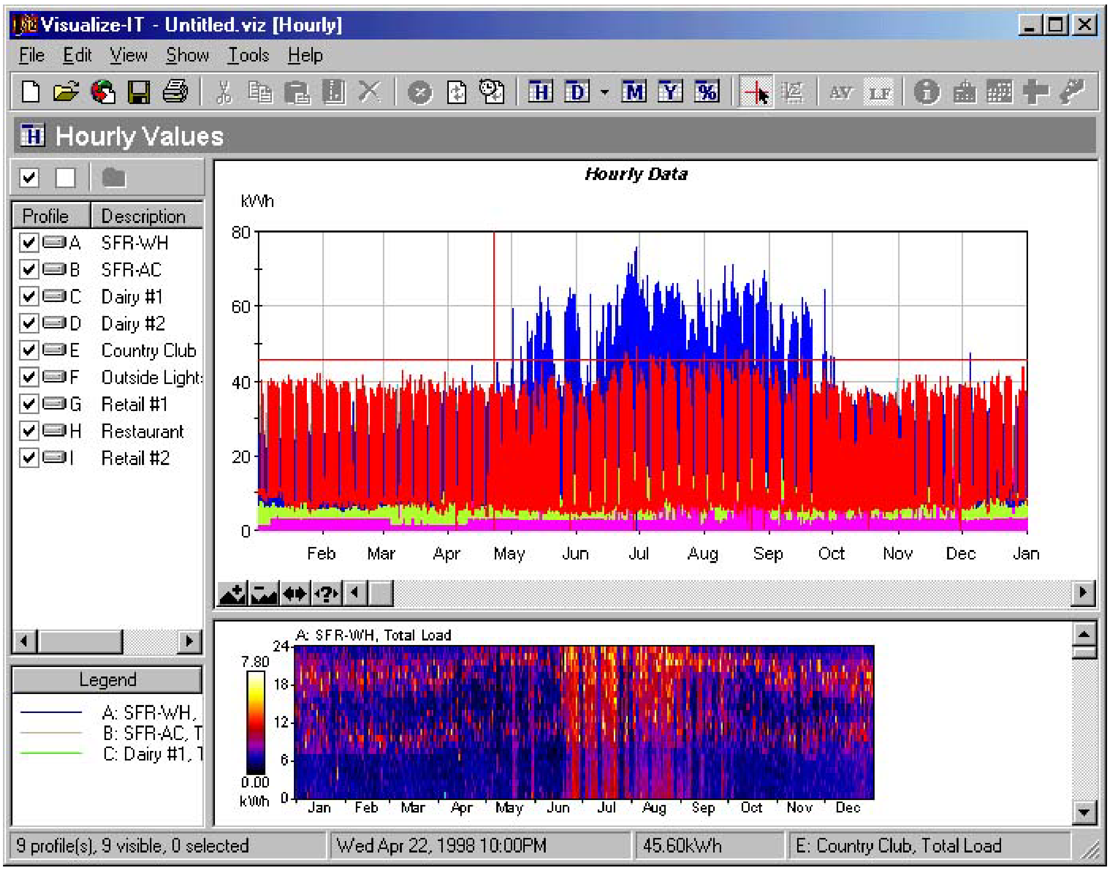
Strengths: Input allows for easy detailing of geometric building model. Access to complex, accurate BLAST models as well as simple presentation of results. Access to all the BLAST libraries and these can be customized to user needs. Customization of necessary Fan System and Plant parameters for the described facility. Context sensitive help for HBLC features. Access to all the BLAST Family of Programs through the HBLC interface. Access to the BLAST Manual (Help file) from within HBLC.

Weaknesses: Some features of BLAST's geometry are not available through this interface.

Visualize-IT Energy Information and Analysis Tool

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Designed to explore, summarize and analyze time series interval data. Visualize-IT has been developed specifically for electric and gas load data, but it is equally useful as a general purpose data visualization tool for other time series measurements such as weather, industrial process control, and water quality.



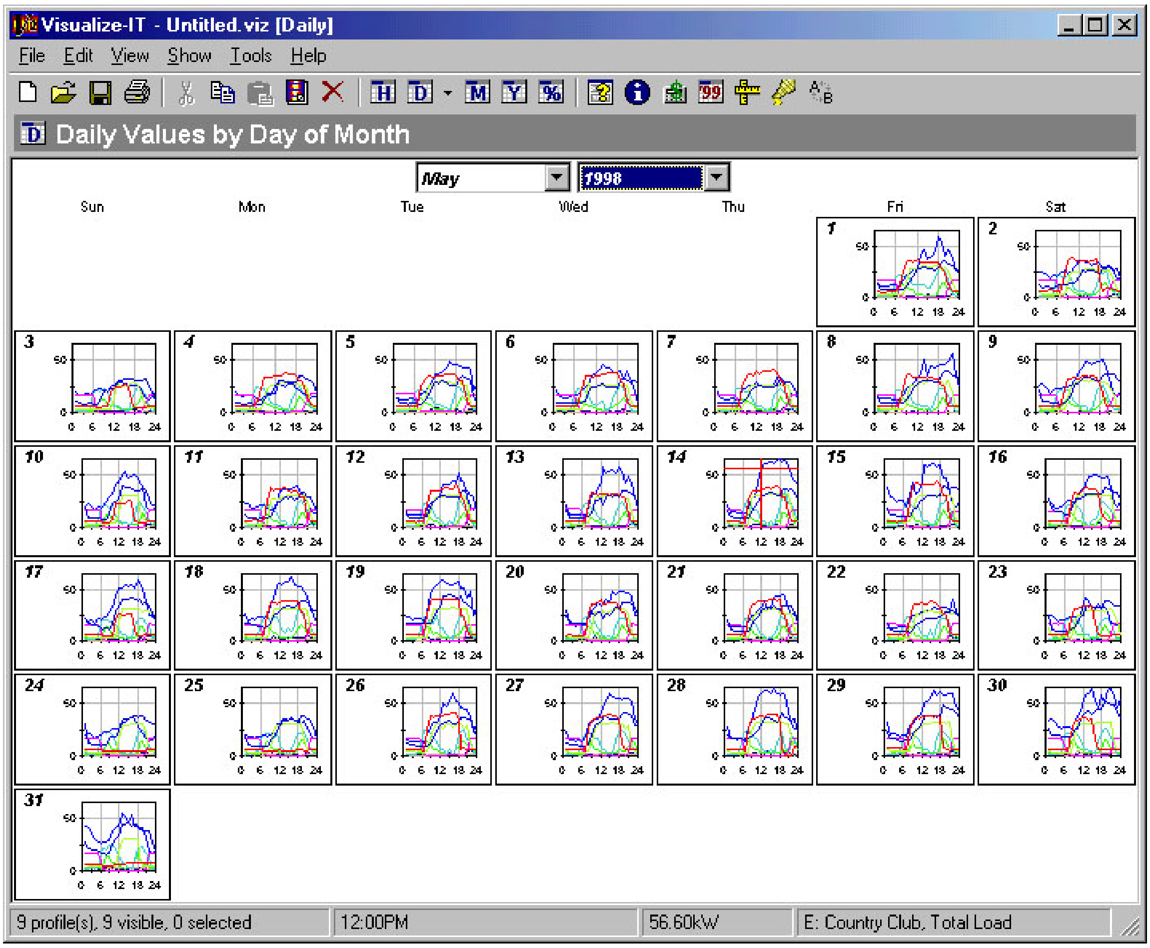
Keywords: energy analysis, rate comparison, load profiles, interval data

Expertise Required: Basic knowledge of energy data analysis and concepts.

Users: Over 100 users internationally.

Audience: Load Researchers, Building Simulation Engineers, Facilities Managers, Energy Account Managers.

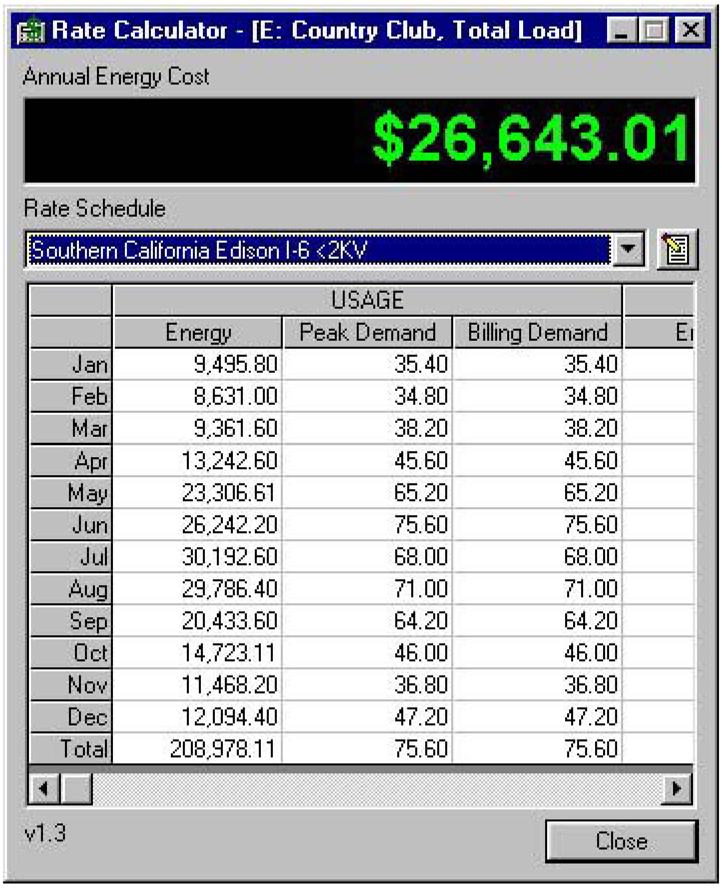
Input: Any type of interval (primarily load) data. Visualize-IT can analyze other types of interval data such as weather, hourly prices, etc. Data formats which are supported are Text, CSV, Binary, DOE-2.1E output files, MV-90 and Loadstar Output files, and real-time data downloaded directly from a number of internet data providers.



Output: Visualize-IT produces numerous interactive charts and Energy Prints, a color map of interval data, with the time of day plotted on the Y axis, the day plotted on the X axis, and the measured value for each interval represented using color. Charting options include: Raw values, Aggregated values (by day, week, month, billing period, etc.), Day Profiles (Average Weekday, Weekend, etc.), Calendar view, Frequency Distribution and Cumulative Distribution (Load Duration) graphs. Various tools operate on the data to scale or true-up profiles, restrict analysis to particular time periods, and provide many other operations. The optional Rate Calculator provides a wizard used to design and analyze rate schedules and energy bills. Data (and graphs) can be copied and pasted directly into other applications. Visualize-IT supports a number of standard export formats as well.

Computer Platform: Windows 95/98/ME/NT and 2000

Programming Language: Visual Basic and C++



Strengths: Data visualization, rate analysis, ability to analyze and compare data with different sample rates, units, time periods and from any number of sources simultaneously.

Weaknesses: Not easily suited to analyzing data with sample rates greater than 1 hour (i.e., daily or monthly data).

Validation/Testing: N/A

ENFORMA

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Includes the MicroDataLogger portable data acquisition equipment and HVAC and Lighting Analyzer software. ENFORMA is designed to cost-effectively gather data and convert it into information about building performance. ENFORMA provides a unique solution that can gather the data at a minimal cost and help you determine solutions to typical building problems. This detailed diagnostic information is the key that allows you to improve upon your current services or expand into new business opportunities. ENFORMA solutions typically result in projects with paybacks of less than one year.

ENFORMA solutions can help you improve upon or begin doing the following services: Performance Guarantees, Comfort Trouble Shooting, HVAC Operation Outsourcing, Commissioning, Accurate Equipment Tune-ups, and Energy Services.

Keywords: data acquisition, energy performance, building diagnostics, HVAC systems, lighting systems

Expertise Required: Knowledge of typical HVAC, lighting or control systems operation is important to understand analysis results. A 2-day training course is available, as well as extensive on-line help, Internet home page technical support, phone support, and tutorial usage manual.

Users: 120 customers of MicroDataLogger data acquisition system, 25 users of ENFORMA software, 95% of customers are in U.S.

Audience: Tool is directed at energy service providers, HVAC service contractors, utilities, and the facility staff of large institutions.

Input: Operating schedule of the building in question, brief description of HVAC systems in building, system performance data from data loggers and building controls system as dictated by software.

Output: Plots of how HVAC, controls, and lighting systems are performing, sample plots that show how systems should be running, time series plots, user defined plots, energy load profiles, and reporting functions to document results of analysis. Software uses various filtering tools to control how data is shown, and automatically calculates deltas, offsets, standard engineering conversions of data streams. The user never has to deal with raw data in complicated spreadsheet sessions.

Computer Platform: 486 or above, running Windows 3.1, or 95.

Programming Language: C++

Strengths: Total integration of the building diagnostic process. Major time and cost savings from having the software define the metering plan, program the loggers, manage the resulting data, and guiding the user towards problem solutions using a built-in engineering knowledge base. Uses actual building system performance data to determine: baseline energy usage, system operation problems, potential maintenance issues, the need for retrofits or equipment replacement, reason for comfort problems, and load shapes for power purchasing.

Weaknesses: Requires the user to take the time to gather actual HVAC, controls, and lighting system performance data using our MicroDataLogger data acquisition system. Does not currently perform automatic system diagnostics, but that capability is in our development plans.

HVACSIM+

Description below taken from http://www.eren.doe.gov/buildings/tools_directory/database

Simulation model of a building HVAC (heating, ventilation, and air-conditioning) system plus HVAC controls, the building shell, the heating/cooling plant, and energy management and control system (EMCS) algorithms. The main program of HVACSIM+ (HVAC SIMulation PLUS other systems) employs a hierarchical, modular approach and advanced equation solving techniques to perform dynamic simulations of building/HVAC/control systems. The modular approach is based upon the methodology used in the TRNSYS program.

Keywords: HVAC equipment, systems, controls, EMCS, complex systems

Expertise Required: High level of computer literacy.

Users: More than 100.

Audience: Building technology researchers, graduate schools, consultants.

Input: Building system component model configuration, simulation setup work file, boundary data file, and simulation control data. Weather data and thermal property data of building shell materials are also required, when building shells are included in a simulation.

Output: User-designed reports.

Computer Platform: PC-compatible, with 640 kilobytes of RAM and math coprocessor.

Programming Language: FORTRAN 77

Strengths: Dynamic response using variable time-steps; flexibility of model setup; interactive simulation model generation; simultaneous non-linear equation solving; stiff ordinary differential equation handling.

Weaknesses: High level of user computer literacy required; long calculation time when solving simultaneous equations.

California Energy Commission
Public Interest Energy Research Program

HPCBS # E5P23T2b

HPCBS

High Performance Commercial Building Systems

Manual of Procedures for Calibrating Simulations of Building Systems

Element 5 - Integrated Commissioning and Diagnostics
Project 2.3 - Advanced Commissioning and Monitoring Techniques

M. Liu
Energy Systems Laboratory, University of Nebraska
D. E. Claridge, N. Bensouda, K. Heinemeier, Seung Uk Lee, and G. Wei
Energy Systems Laboratory, Texas A&M University

October, 2003

Acknowledgement

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MANUAL OF PROCEDURES FOR CALIBRATING SIMULATIONS OF BUILDING SYSTEMS

Prepared by:

David E. Claridge, Nabil Bensouda, Seung Uk Lee, and Guanghua Wei
ENERGY SYSTEMS LABORATORY, TEXAS A&M UNIVERSITY

Kristin Heinemeier
BROOKS ENERGY & SUSTAINABILITY LABORATORY, TEXAS A&M UNIVERSITY
and
Mingsheng Liu
ENERGY SYSTEMS LABORATORY, UNIVERSITY OF NEBRASKA

For:

LAWRENCE BERKELEY NATIONAL LABORATORY

OCTOBER 2003

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DISCLAIMER

This report was prepared by the Energy Systems Laboratory (ESL) of the Texas Engineering Experiment Station (TEES) and the Energy Systems Laboratory of the University of Nebraska (UN) and was sponsored by the California Energy Commission (CEC) Public Interest Energy Research Program through the High Efficiency Commercial Buildings Project at the Lawrence Berkeley National Laboratory (LBNL). Neither the ESL, TEES, UN, CEC or LBNL or any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe on privately-owned rights.

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EXECUTIVE SUMMARY

The calibration of a cooling and heating energy simulation for a building to measured heating and cooling consumption data has been shown to be valuable for predicting the energy savings possible from operational changes and retrofits. It is also recognized as an important way of baselining energy consumption to determine savings from retrofits. However, the calibration processes used to achieve agreement have generally been quite time-consuming.

This manual presents a methodology for the rapid calibration of cooling and heating energy consumption simulations for commercial buildings based on the use of "calibration signatures", that characterize the difference between measured and simulated performance. The method is described and then its use is demonstrated in two illustrative examples and two real-world case studies. This document contains characteristic calibration signatures suitable for use in calibrating energy simulations of large buildings with four different system types: single-duct variable-volume, single-duct constant-volume, dual-duct variable-volume and dual-duct constant-volume. Separate sets of calibration signatures are presented for each system type for the climates typified by Pasadena, Sacramento and Oakland, California.

I. BACKGROUND AND OVERVIEW

1. Calibrated simulation

Need for Calibration

Energy simulation has been an important part of building science research, as well as implementation of energy efficiency improvements. Available simulation tools include detailed whole building simulations (such as DOE2 and BLAST), detailed system simulations (HVACSIM+) and simplified models (ASEAM and AirModel). Historically, the inputs for energy simulations of commercial buildings have been based on design data. The experience of the authors and others who have performed hundreds of energy simulations indicates that differences of 50% or more between simulation results based on design data and measured consumption are not unusual. These errors are not thought to be due to errors in the simulation software itself, but to errors in the input assumptions for a particular building, due to misunderstanding of the building's design or to the differences between design and as-built conditions or operations.

Consequently, numerous organizations and individuals have developed procedures to adjust the inputs used to "calibrate" a simulation so the simulated results more closely match measured consumption (e.g. Diamond and Hunn 1981, Kaplan et al. 1992, Haberl and Bou-Saada 1998 and Liu and Claridge 1998). These procedures employ a variety of techniques to either measure or infer the characteristics of individual buildings as they were built and operated and identify candidate changes in model inputs that may resolve the differences. These efforts have been quite successful in achieving simulated results that agreed with the measured consumption, typically to less than 5% on an annual basis. Agreement within 5-10% has often been achieved on a monthly basis, and sometimes on a daily basis. Once a probable error (or errors) in a simulation input has been identified, the analyst must typically assess whether the change makes physical and intuitive sense. This sometimes requires revisiting the building or conducting some other investigation. It must then be decided whether it is appropriate to revise the model inputs before accepting the model.

Uses of Calibrated Simulation

The calibration processes used to achieve agreement have generally been quite time-consuming and required a great deal of specialized expertise. There would be tremendous value in having a procedure that can quickly and reliably calibrate simulations of large commercial buildings with built-up HVAC systems. Then, it would be practical to use a calibrated simulation for many different uses. There has been an increased level of interest in applications for calibrated simulation in recent years (IPMVP 2001, Liu and Claridge 1998). Uses for calibrated simulation include:

- energy audits, to determine the potential savings from proposed retrofit measures;
- energy savings determination after retrofits
- energy savings estimation, to explore the potential savings from changing building operational strategies ("what-if" analysis);
- existing building and new construction commissioning;
- fault detection and diagnostics
- model-based optimization; and

- program evaluation.

Calibrated simulation received a significant boost by inclusion as one of the approved methods for establishing energy baselines for savings determination in the *International Performance Measurement and Verification Protocol* (IPMVP 2001).

Data Used for Calibration

A simulation that will be useful for large commercial buildings with built-up HVAC systems can require hundreds of input variables, and will have at least a few dozen crucial input parameters. If monthly values of measured consumption data were used for calibration, there would be more parameters that may be varied than the number of data points being fit with a typical year of data and the problem would be mathematically "over-determined" (more equations than unknowns). This has the consequence that the calibration achieved might fit past data very well, but will not necessarily fit future data very well. Hence, a calibration based on monthly data is not suitable for use in tuning HVAC operating parameters. The use of several months of daily consumption data eliminates this problem and has been shown to be suitable for use in calibrating models that were subsequently used to develop improved operating strategies (Liu and Claridge 1998). Hourly data can also be used, although dynamic effects of the thermal mass of the building and system will become evident. In some calibration methods, this could present a problem, although the differences will tend to average out over the course of a day, so some statistical analysis will not be affected by these differences. Hourly data can also be used to "fine tune" a calibration that was done mostly with daily data (Liu, Wei and Claridge 1998). This is achieved by introducing a daily load profile as shown in the two case studies in this report.

The simulation period should cover most of the annual ambient temperature range. It may vary from several weeks to a whole year depending on the fluctuations of weather conditions throughout the year.

The measured performance data used for calibration must closely match the simulated data when calibration is complete. It must include the same physical factors (e.g. thermal load or energy consumption, whole building or system-based, hourly, daily or monthly) over the same period of time. Often, either the measured or simulated data can be aggregated or disaggregated in order to perform the necessary comparison. Measured data can be obtained from any of a number of sources:

- Utility billing data (typically monthly, or something close to monthly).
- Utility interval meter data (available from the utility for some larger buildings).
- Interval pulse-data obtained from a utility meter.
- Data from an Energy Management and Control System.
- Data from an installed data logger (with Btu or kWh sensors/transducers).

Data quality must be assessed for any use of measured data. Identifying erroneous data points is important. Particularly for shorter interval data, an approach to identifying and "fixing" any erroneous or missing data must be designed: in some cases, it is appropriate to interpolate to fill any holes in the data, while in other cases it is best to simply eliminate those data points from the analysis.

2. Overview of the calibration signature method and this manual

This manual presents an improved method of calibrating simulations – the calibration signature method. Experienced users of the method can calibrate a two-zone simulation of a building with large built-up systems in 10-40 hours. The approach has also been used by students to complete calibrations as course project assignments in a graduate building systems course at Texas A&M.

The method is based on a unique graphical representation of the difference between the simulated and measured performance of a building, referred to as a "Calibration Signature". For a given system type and climate, the graph of this difference has a characteristic shape that depends on the reason for the difference. For example, for a single-duct variable-air-volume system in Pasadena, if the cooling coil temperature is one degree lower in the real building than was assumed in the simulation, the shape of the calibration signature will look very similar to the graphs shown at the top of Appendix D-1. These "characteristic" calibration signatures (or "characteristic signatures") can be produced for a given system type and climate and published. By matching the observed signature with the published characteristic signature, the analyst is given clues to the factors that may be contributing to the errors he or she is observing.

This manual describes the use of the calibration signature method. It shows how the calibration signature is defined and how it can be calculated for a given building. It describes how characteristic signatures were derived for a set of system types and climates. The process for using these characteristic signatures as an aide in calibration is then described. A series of examples help to describe the use of these signatures and to illustrate some of the decisions that must be made. In the Appendices, characteristic calibration signatures are presented for the following system types and climates.

System Types:

- Single-Duct Constant-Air-Volume (SDCV).
- Single-Duct Variable-Air-Volume (SDVAV).
- Dual-Duct Constant-Air-Volume (DDCV).
- Dual-Duct Variable-Air-Volume (DDVAV).

California Climates:

- Pasadena.
- Sacramento.
- Oakland.

II. CALIBRATION USING CHARACTERISTIC SIGNATURES

The calibration procedure presented in this manual is based on the use of "characteristic signatures". Wei et al. (1998) found that calculating the difference between the measured heating or cooling consumption and that predicted by an un-calibrated simulation, normalizing them and plotting them as a function of ambient temperature, provides important information about the input variable change(s) needed to achieve calibration. This type of plot has been termed a "calibration signature". By publishing characteristic signatures, a useful clue is provided to anyone intending to calibrate a simulation.

This section presents the definitions of the calibration signature, the characteristic signature, and two statistical variables used to evaluate calibrated simulations. It also presents a detailed step-by-step calibration procedure and a description of the published characteristic signatures and their climate dependence.

1. Definition of the calibration signature

The calibration signature is a normalized plot of the difference between measured energy consumption values and the corresponding simulated values as a function of outdoor air temperature. This is typically calculated on a daily average basis, but other time steps can be used as well. The energy consumption values can be whole building or system consumption, and they can be electric (kWh) or thermal (e.g. chilled water consumption in MMBtu). The calibration signature value for heating or cooling energy consumption is calculated as follows:

$$\textit{Calibration signature} = \frac{-\,\textit{Residual}}{\textit{Maximum measured energy}} \; x\ 100\ \% \qquad (1)$$

where

$$\textit{Residual} = \textit{Simulated consumption} - \textit{Measured consumption} \qquad (2)$$

and the denominator is the maximum measured cooling or heating consumption, respectively for a cooling or heating calibration signature, determined over the entire range of outside air temperatures contained in the data file being used.

Figure 1 shows a calibration signature plot for hot water (HW) energy use. Note that this signature always has positive values, it decreases with increasing outside air dry-bulb temperature (T_{db}) and reaches zero at about 80°F. These characteristics will be useful in trying to determine what errors were present in the simulation inputs.

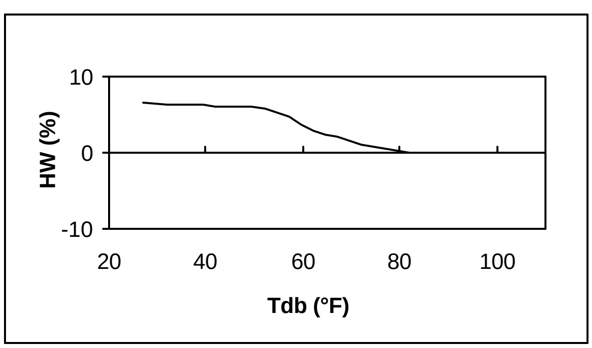


Figure 1. Example of a heating calibration signature

2. Definition of the characteristic signature

Any particular uncalibrated (or partially calibrated) simulation will have a calibration signature, as described in the previous section. However, the errors in the simulation inputs that are responsible for the residuals between measured and simulated data will cause a predictable shape for the calibration signature. If you compare the results from your simulation with a published calibration signature, and its shape matches, you will have found a clue in what simulation input parameter to change to improve your simulation.

These characteristic calibration signatures can be calculated using simulation programs. This is done by simulating the building with one value for an input parameter (the "baseline" run), then changing that input parameter by a given amount and rerunning the simulation. The "residuals" between these two simulations are calculated, normalized, and plotted versus outdoor air temperature, just as was done to calculate a calibration signature for a particular uncalibrated simulation with measured data. The formula for calculating this characteristic calibration signature is as follows:

$$\textit{Characteristic signature} = \frac{\textit{Change in energy consumption}}{\textit{Maximum energy consumption}} \; x\ 100\ \% \qquad (3)$$

where the change in energy consumption is taken as the cooling or heating energy consumption value from the simulation with the changed input minus the baseline value at the same temperature. The denominator is the maximum baseline cooling or heating consumption, respectively for a cooling or heating characteristic signature, determined over the entire range of outside air temperatures contained in the weather file being used.

This definition then shows all changes in terms of the percent change relative to the maximum value of the cooling required in the baseline case for the cooling characteristic signature, or the maximum baseline heating consumption for the heating characteristic signature. These signatures also represent a parametric sensitivity analysis for the building and system of interest.

Figure 2 shows cold deck temperature (T_c) characteristic calibration signatures for cooling and heating. The curve on the left shows the change in chilled water (CHW) energy use and the curve on the right the change in hot water (HW) energy use, when the temperature at which air leaves the cooling coil was decreased from 55 to 53°F.

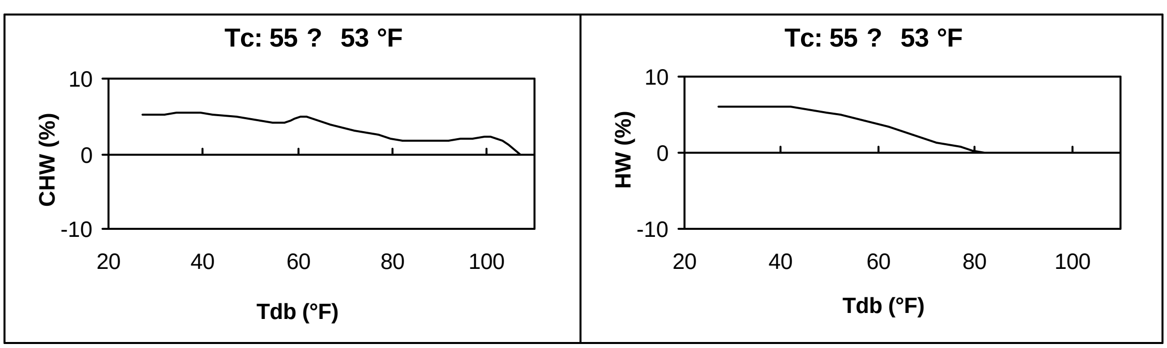


Figure 2. Cold deck temperature characteristic calibration signatures

If we were attempting to calibrate the simulation with the heating calibration signature shown in Figure 1, it is clear that this calibration signature matches the heating characteristic signature in Figure 2, so the best input variable to change is the cold deck temperature. Since the characteristic signature is the result of reducing the coil temperature by two degrees, the temperature used as input for the simulation should also be reduced by about two degrees to eliminate this error.

The clues provided by the characteristic calibration signatures are much clearer when you use both cooling and heating calibration signatures. These two will typically show very different trends, and the combination can be a powerful indicator of the input parameter that needs to be changed.

3. Weather Implications

The characteristic signatures shown in Figure 2 clearly depend on outside temperature. Though not explicitly shown, they also depend on the ambient humidity level when it is high enough to induce latent cooling loads. This is treated by simply using the mean of the humidity values present at each temperature in the weather data for the site in question to define the characteristic signatures. This humidity dependence suggests that separate sets of signatures may be needed for sites with significantly different temperature and humidity combinations. Separate sets of signatures are also required for different air handler types.

Characteristic signatures depend on the correlation between relative humidity and dry-bulb temperature for the location of interest. Figure 3 shows the average measured relative humidity as a function of ambient temperature for the three California cities used to generate the sets of characteristic signatures presented in this manual. The weather data used was provided by Motegi (Motegi, 2001). Dry-bulb temperatures in the data sets used range from 33 °F to 97 °F, 27 °F to 105 °F and 35 °F to 83 °F respectively for Pasadena, Sacramento and Oakland. Relative humidity ranges from 30 to 81%, 22 to 85% and 40 to 91% respectively.

We notice that Sacramento has the widest ranges of both temperature and relative humidity. It is the coldest city in the winter and the hottest in the summer. Oakland has the narrowest ranges of temperatures and relative humidity. It is the warmest in the winter and the coolest in the summer. Pasadena weather conditions fall between the extremes of the weather conditions of the other two cities.

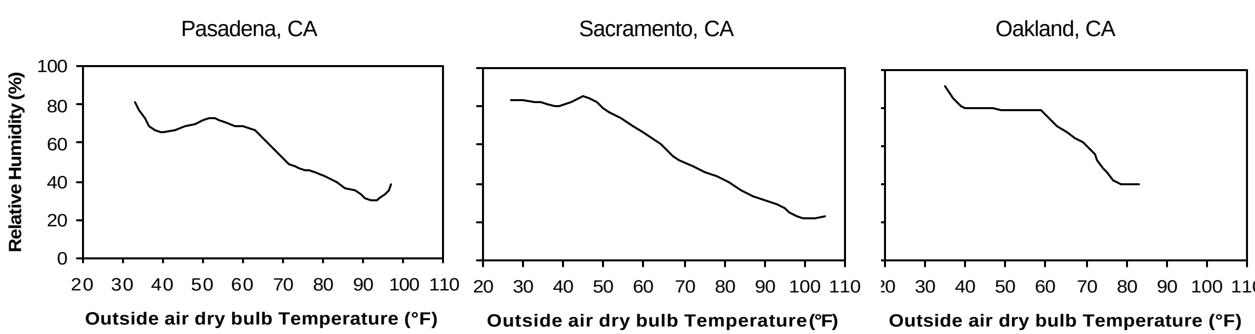


Figure 3. Weather data for three representative California cities

4. Evaluating the Adequacy of a Calibration

There are several metrics to use in evaluating whether or not a simulation is sufficiently calibrated, or in comparing two possible calibration adjustments.

- **Root Mean Square Error (RMSE)**, defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} Residual_i^2}{n-2}} \tag{4}$$

where n is the number of data points. The RMSE is a good measure of the overall magnitude of the errors. It reflects the size of the errors and the amount of scatter, but does not reflect any overall bias in the data. For example, if large errors are randomly distributed both above and below zero, you would have a large RMSE. Similarly, if all the errors are positive, you might have the same RMSE. Thus, the RMSE would be a good metric of how "good" the simulation is for calibration purposes. In the authors' experience, it is generally difficult to achieve a value of the RMSE that is less than 5 to 10% of the mean value of the larger of the heating and cooling consumption. The minimum RMSE will sometimes be significantly larger, particularly when heating and cooling consumption are small relative to total internal gains.

- **Mean Bias Error (MBE)**, defined as:

$$MBE = \frac{\sum_{i=1}^{n} Residual_i}{n} \tag{5}$$

where n is the number of data points. With the MBE, positive and negative errors cancel each other out, so the MBE is an overall measure of how biased the data is. The MBE is also a good indicator of how much error would be introduced into annual energy consumption estimates, since positive and negative daily errors are cancelled out.

A simulation with a small RMSE, but with a significant MBE, might indicate an error in simulation inputs. A simulation with a large RMSE but a small MBE, might have no errors in simulation inputs, but building performance may reflect some other un-modeled behavior (such as occupant behavior) that is difficult to simulate, or it may have significant input errors. Minimizing mean bias error is very important if a calibrated simulation is to be used as a baseline for determining savings from retrofits or commissioning.

Calibration using characteristic calibration signatures involves estimating both cooling and heating energy use. A separate RMSE can be calculated for each. It is common that making a specific change to simulation inputs will increase a heating RMSE while decreasing a cooling RMSE, or vice versa. In this case, the two RMSE values may be summed, and a minimum value may be sought.

5. Published characteristic signatures

This manual provides characteristic signatures for single-duct constant-air-volume (SDCV), single-duct variable-air-volume (SDVAV), dual-duct constant-air-volume (DDCV) and dual-duct variable-air-volume (DDVAV) air handling Units (AHUs). The signatures are given for three representative climates in California: Pasadena, Sacramento and Oakland. The most commonly used AHUs in California appear to be variable-air-volume (VAV) systems. Characteristic signatures for the four major AHU system types are produced and discussed in this manual.

Separate characteristic signatures are prepared for each parameter that has been found to be of major importance in calibrating a simulation, as shown below:

- Cold deck temperature
- Hot deck temperature (DD systems)
- Supply air flow rate (for CV systems)
- Minimum air flow rate (VAV systems)
- Floor area
- Preheat temperature
- Internal gains
- Outside air flow rate
- Room temperature
- Envelope U-value
- Economizer

These parameters were selected as those that have a significant influence on energy consumption, those that are perceived as having a significant influence (and thus are commonly considered for making calibration changes) and those in which the authors have frequently seen errors.

The characteristic signatures in this manual were created by simulating a simple building, and then altering one of the key input parameters and then calculating and plotting their characteristic calibration signatures. Appendix A describes the building and system models that were used to create the signatures.

Sets of characteristic signatures are available in appendices C, D, E and F respectively for SDCV, SDVAV, DDCV and DDVAV systems. Each appendix has sets of signatures for Pasadena, Sacramento and Oakland, California. The left-hand column shows the chilled water (CHW) characteristic signature and the right-hand column shows the hot water (HW) characteristic signature for the input variable noted in each figure.

The characteristic signatures were generated using AirModel, an HVAC software package for simulation of building cooling and heating consumption. AirModel is based on the ASHRAE Simplified Energy Analysis Procedure (Knebel 1983) was developed at the Energy Systems Laboratory at Texas A&M University (Liu et al., 1997). The signatures and calibration methodology may also be used with other simulation packages that can provide daily values of heating and cooling consumption.

In some cases, it may be feasible and preferable for an analyst to create his or her own characteristic signatures, using the simulation to be calibrated as the baseline. This may be a convenient way to summarize the possible adjustments that can be made and to organize a selection process. The process for doing this is described in Appendix G.

6. Calibration using characteristic signatures

The steps to follow to calibrate cooling and heating simulations using characteristic signatures are as follows:

Step 1. Collect measured consumption and weather data over a period of uniform HVAC system operation.

Step 2. Perform an initial simulation using the best estimates of your system parameters.

Step 3. Make any necessary conversions of weather data, measured consumption data and simulated results to daily averages or another time step, or temperature bins. It may be necessary to adopt guidelines to deal with missing measured data (e.g. interpolate up to a critical number of missing data points per time step and disregard the whole time step if more data points are missing).

Step 4. Calculate the residuals, the RMSE and the calibration signature according to equations 2, 4 and 1.

Step 5. Plot measured data, simulated results and residuals in the same chart as a function of outside air dry-bulb temperature and plot the calibration signature on the same or a separate chart. It may be helpful to perform some type of best fit regression to the calibration signature data points to help detect the overall trend of the signature.

Step 6. Compare cooling and heating calibration signatures with the characteristic signatures available in appendices C, D, E or F for the corresponding system type and climate and try to find the best match or matches. If there is a need to create your own characteristic signatures for other weather conditions or other variations of air handling unit types or to test the sensitivity of other input parameters not tested in the signatures provided, follow the procedure described in appendix G. In comparing the pair of cooling and heating calibration signatures with pairs of cooling and heating characteristic signatures, things to look for include intercepts, slopes and bulges. This will identify an input or inputs that, when changed, are the most likely to minimize the residuals over the targeted range or ranges of outside air temperature.

If two or more pairs of characteristic signatures have similar shapes (e.g. the floor area and the total supply air characteristic signatures in appendix C-1), conduct field measurements or use your own judgment to estimate which one is the most likely to be inaccurate in the initial simulation. It's possible that more than one needs to be changed.

If the calibration signatures do not strongly resemble any pair of characteristic signatures, try to use characteristic signatures to reduce cooling and heating calibration signatures at their maximum magnitudes or to remove any irregular shapes in either calibration signature over a certain range of outside air temperature. It is possible to alter two or more inputs simultaneously when each one of them targets a different range of outside air temperature or targets more specifically either the cooling or the heating calibration signature.

Step 7. Alter the identified input parameter and rerun the simulation. The change should be made in the same direction as in the identified pair of characteristic signatures (e.g. increase or decrease). The amount of change should be estimated by comparing the magnitudes of the cooling and heating calibration signatures with the magnitudes of the cooling and heating characteristic signatures. Different values may be tested and the value with optimum results can be selected.

Step 8. Evaluate the new RMSE, residuals and cooling and heating calibration signatures. If the results of the calibration are not satisfactory, repeat from step 6 and iterate until the RMSE is minimal, the residuals are randomly scattered around zero and the calibration signature is flat and shows no trend with temperature.

Step 9. If daily data was used for the calibration, fine-tune the calibration by calibrating the simulation of hourly data. This can be achieved by introducing a daily load profile describing load variation during HVAC operating hours.

7. Applications of the Calibration Signature Method and Precautions

This approach to calibrated simulation has been used by the Energy Systems Laboratory (ESL) for several years in different applications. It has been used for diagnostics and prediction of the savings to be expected from commissioning projects. Table 1 compares calibrated simulation values of three system temperatures with site measured values and EMCS set points (Liu et al. 2002). The calibrated simulation predicted savings of $191,000 from commissioning this building with measured savings of $200,000. The process is fast enough that that it has been used to predict savings from commissioning measures in dozens of buildings in a variety of contracted commissioning jobs. Some of this work is described in Liu and Claridge (1995, 1998) and in Turner et al. (2003).

Table 1. Comparison of calibrated values of simulation parameters with site measured values and EMCS set points.

	Pre-cooling deck	Cold deck	Hot deck
"Calibrated" Value	52.0°F	52.0°F	85.0°F
Site Measured	52.8°F	51.5°F	85.0°F
EMCS Set Point	60.0°F	55.0°F	80.0°F

Calibrated simulation was used in five buildings in a study on the persistence of savings from commissioning. In this study, component failures in one building prevented accurate calibration, but in the remaining four buildings, consumption changes over a two year period were shown to closely agree with changes due to documented control changes in the buildings. (Turner et al., 2002, Claridge et al. 2002, Cho, 2002)

Calibrated simulation requires relatively detailed information about the building. It is advisable to check the calibrated values against values measured in the building when possible, particularly if the calibrated values differ significantly from the expected values. A calibrated simulation cannot accurately represent a building if the simulation is not capable of modeling an important phenomenon affecting the operation of the building. Factors such as duct leakage, terminal box leakage, and valve leakage are commonplace in buildings but are not commonly modeled by simulation programs.

The level of effort expended on calibration may be influenced by the intended use of the simulation. If the simulation will be used to project the impact of specific operational changes in a building, emphasis should be placed on accurately modeling the portions of the system that will undergo changes.

III. EXAMPLES OF USE OF CHARACTERISTIC SIGNATURES

Two examples are presented to illustrate the application of the calibration process described in section II.6. The first example illustrates the basic calibration steps using the signatures. The second is a more complex example in which more judgment must be used to perform the calibration. Both examples are based on a simulated building (i.e., the "measured" data used for the calibration is actually output from a simulation). The case studies presented in section IV show the use of this method with data from real buildings.

The two examples that follow use the building and DDCV system described in Appendix B. They were simulated using AirModel and Pasadena weather data.

1. Simple Example

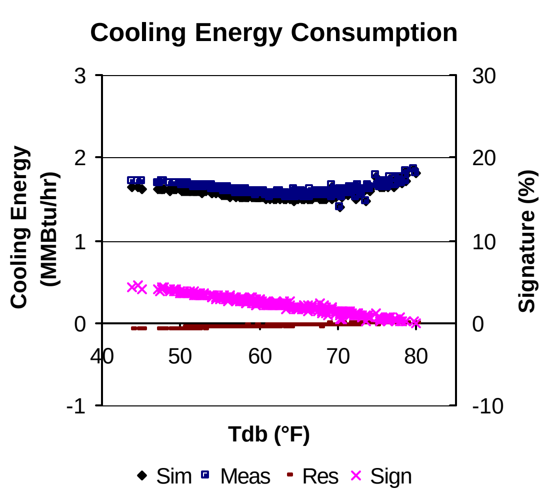
Step 1. The results of an "accurate" or "baseline" simulation were used in this example as the "measured" data. Then, a set of "errors" was introduced into the simulation inputs to represent an uncalibrated simulation. The example illustrates the use of characteristic signatures to identify what these errors were. Pasadena weather data will be used.

Step 2. The uncalibrated simulation was conducted with hourly data.

Step 3. Hourly weather and cooling and heating data were converted to daily averages.

Step 4. The residuals, the RMSE and the calibration signatures were calculated for the initial simulation. The RMSE was found to be 0.05 MMBtu/hr and 0.07 MMBtu/hr respectively for cooling and heating energy consumption.

Step 5. Measured data (Meas), simulation results (Sim), residuals (Res) and calibration signatures (Sign) were plotted versus outside air dry-bulb temperature (T_{db}), as shown in Figure 5, for cooling (left) and heating (right). The signature magnitudes are shown on the right hand side y-axis. Note that the symbols for the simulated and measured results overlap, so they cannot be readily distinguished over much of the range.



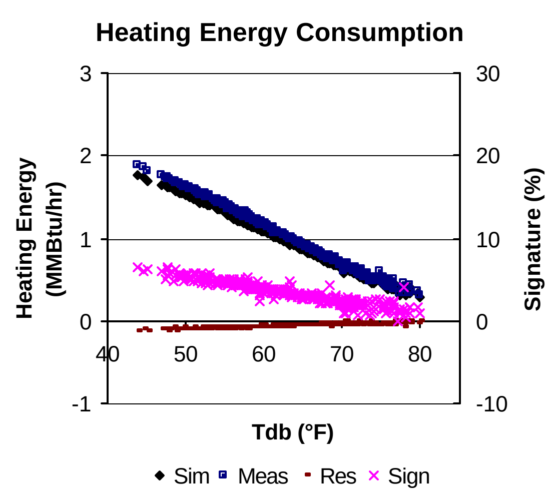


Figure 5. Initial simulation for Example 1 including calibration signatures

Step 6. The calibration signatures in Figure 5 should be compared to the characteristic signatures in Appendix E-1 corresponding to DDCV systems in Pasadena. We notice that the calibration signatures have positive values and negative slopes. They start at about 4% and 7% at low temperatures respectively for cooling and heating energy consumption, and approach zero at higher temperatures. We notice that they are comparable to the characteristic signatures of cold deck temperature, supply air flow rate and floor area for the characteristic signatures of Appendix E-1. Floor area was excluded because the cooling energy signature does not approach zero at high temperatures. In a real building simulation, site measurements of cold deck temperature and supply air flow may be used to determine which was not simulated accurately in the initial simulation. In this illustrative example, it was decided to change the cold deck temperature.

Step 7. In the characteristic signature of Appendix E-1, the cold deck temperature was decreased by 2 °F, which caused an increase of about 7% at low temperatures for both cooling and heating. Since the increase is of about 4% and 7% respectively for the cooling and heating calibration signatures, the cold deck temperature should be decreased by about 1 to 2 °F. Different values between 53 °F and 54 °F were tested during the first iteration and the cooling and heating RMSE values were summed and a minimal value was sought. The best result was obtained by decreasing the cold deck temperature from 55 to 53.6 °F.

Step 8. After this change, the RMS errors have both dropped considerably to 0.020 MMBtu/hr and 0.016 MMBtu/hr respectively for cooling and heating energy consumption. Figure 6 shows simulation charts after this first iteration.

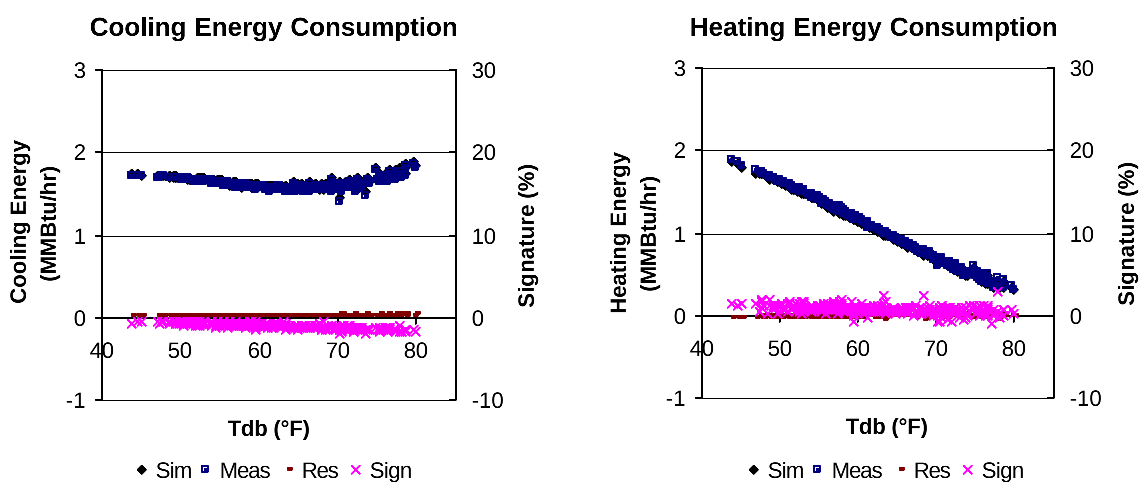


Figure 6. Simulation charts for Example 1 after the first iteration

The choice of the above mentioned value of the cold deck temperature was aimed to optimize both RMS errors for cooling and heating energy consumption. A higher value of 53.8 °F gave RMS errors of 0.013 and 0.024 MMBtu/hr, and a lower value of 53.4 °F gave RMS errors of 0.028 and 0.010 MMBtu/hr, respectively for cooling and heating energy consumption. The results of these simulations are shown in Figures 7 and 8.

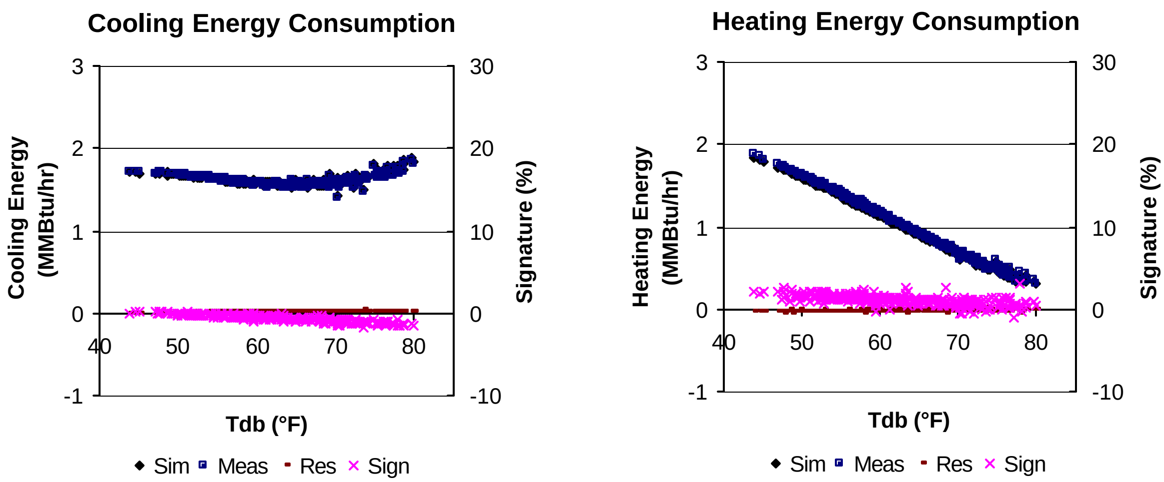


Figure 7. Simulation charts for Example 1 during first iteration with T_C = 53.8 °F

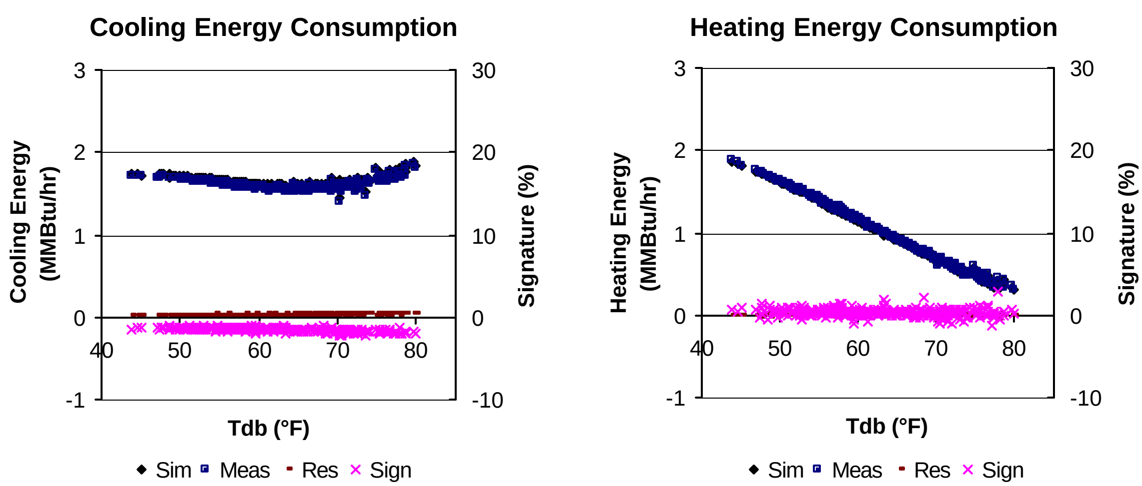


Figure 8. Simulation charts for Example 1 during first iteration with T_C = 53.4 °F

After the first iteration of the calibration process, the calibration signatures show improvement, but there are still significant errors, and the shape of the calibration signatures still show a detectable trend.

Iteration 2. The calibration signatures in Figure 6 have negative values for cooling and positive values for heating. They have negative slopes and approach zero at low temperatures for cooling, and at high temperatures for heating. Referring again to Appendix E-1, we notice that the characteristic signatures for decreasing the internal gain have the same characteristics. In the characteristic signature, a decrease of 0.4 W/ft^2 in internal gains caused maximum changes of about -9% and 7% respectively in cooling and heating energy use. The magnitude of the calibration signatures in Figure 6 reaches about –2% and 2% respectively for cooling and heating energy use, so internal gains should be decreased by about 0.1 W/ft^2. Different values between 0.65 and 0.85 W/ft^2 were tested and the best result was obtained by decreasing internal gains from 0.8 to 0.72 W/ft^2.

After this iteration, the calibration signatures and RMS errors dropped to zero. Figure 9 shows calibrated simulation charts.

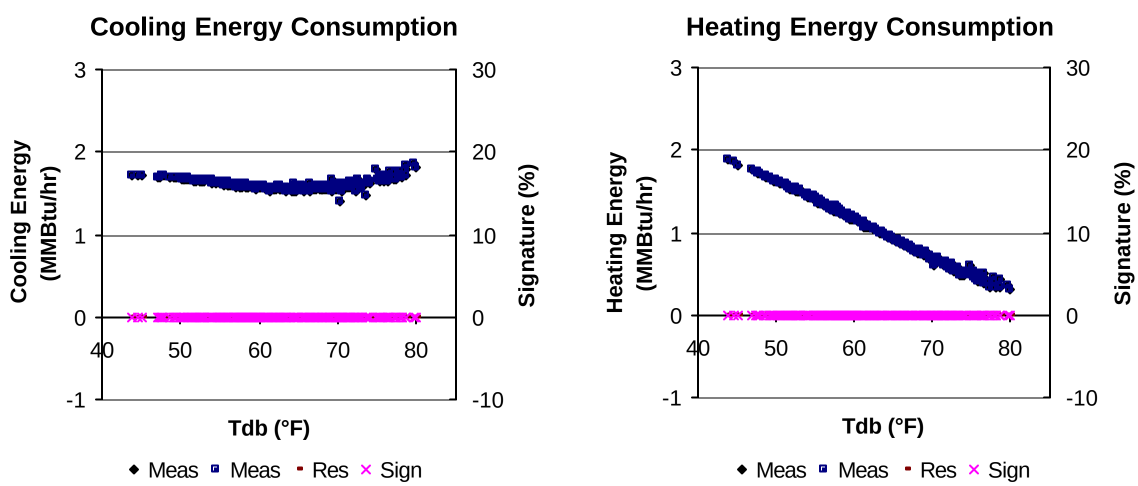


Figure 9. Calibrated simulation for Example 1

2. More complex example

This example utilizes the same building, system used in the previous example and described in Appendix B. In this example, a more complex set of differences were introduced into the "uncalibrated" simulation to increase the difficulty of the calibration process. In addition, the person who devised the baseline simulation that produced the synthetic "measured" data was not the same individual who conducted the calibration. It was therefore possible at the end of the process to compare the final inputs that were selected through the calibration process with the "real" inputs that had been used, and to comment on how successfully the simulation was calibrated.

Step 1. The results of a "baseline" simulation were used in this example as the "measured" data. Then, the individual who conducted the calibration was given a different set of inputs as the inputs for the "uncalibrated" simulation. The example illustrates the use of characteristic signatures to identify the changes needed to calibrate the simulation. Pasadena weather data was used.

Step 2. The uncalibrated simulation was conducted with hourly data.

Step 3. Hourly weather and cooling and heating data were converted to daily averages.

Step 4. The residuals, the RMSE and the calibration signatures were calculated for the initial simulation. The RMSE was found to be 0.07 MMBtu/hr and 0.18 MMBtu/hr respectively for cooling and heating energy consumption.

Step 5. Measured data (Meas), simulation results (Sim), residuals (Res) and calibration signatures (Sign) were plotted versus outside air dry-bulb temperature (T_{db}), as shown in figure 10, for cooling (left) and heating (right). Signature magnitudes are shown on the right hand side y-axis.

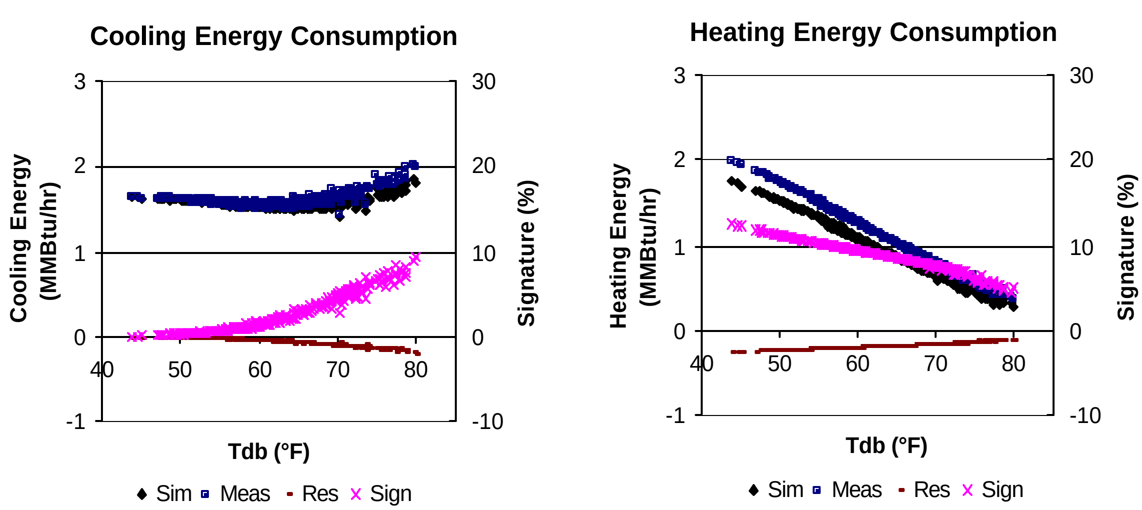


Figure 10. Initial simulation for Example 2 including calibration signatures

Step 6. We examine the calibration signatures of the first simulation as shown in Figure 10. We note that the cooling signature is almost 10% at high temperatures, but close to zero at low temperatures. While the heating signature always has significant positive values, it has the opposite slope. Examining the characteristic signatures in Appendix E-1, we see that only outside air and envelope U-value have this combination of opposite slopes. Neither has a strong positive value throughout the range of outside temperatures, so we assume the calibration signatures represent a combination of multiple characteristic signatures. We choose to modify the outside air quantity, since both calibration signatures reach large values at extreme temperatures, more like those of the outside air signatures than the envelope U-values.

Step 7. In the characteristic signature of Appendix E-1, the outside air flow rate was increased by 0.05 cfm/ft^2, which caused an increase of about 15% in cooling and a decrease of about 8% in heating across the entire range of ambient temperature. In the calibration signatures the change was about 10% and -8% respectively for cooling and heating. This suggests that the outside air flow rate should be increased by about 0.05 cfm/ft^2 or less. Different increments ranging from 0.02 to 0.06 cfm were tested and the best result was obtained by increasing the outside air flow rate from 0.10 to 0.14 cfm/ft^2.

Step 8. After this change, the calibration signature approached zero at high temperatures for cooling, but increased at low temperatures. The cooling RMSE remained at 0.07 MMBtu/hr, but the signature became more uniform across the entire temperature range. For heating, the signature is noticeably smaller at low temperatures, but has changed little at high temperatures. The heating RMSE decreased from 0.18 to 0.16 MMBtu/hr. Figure 11 shows simulation charts after this first iteration.

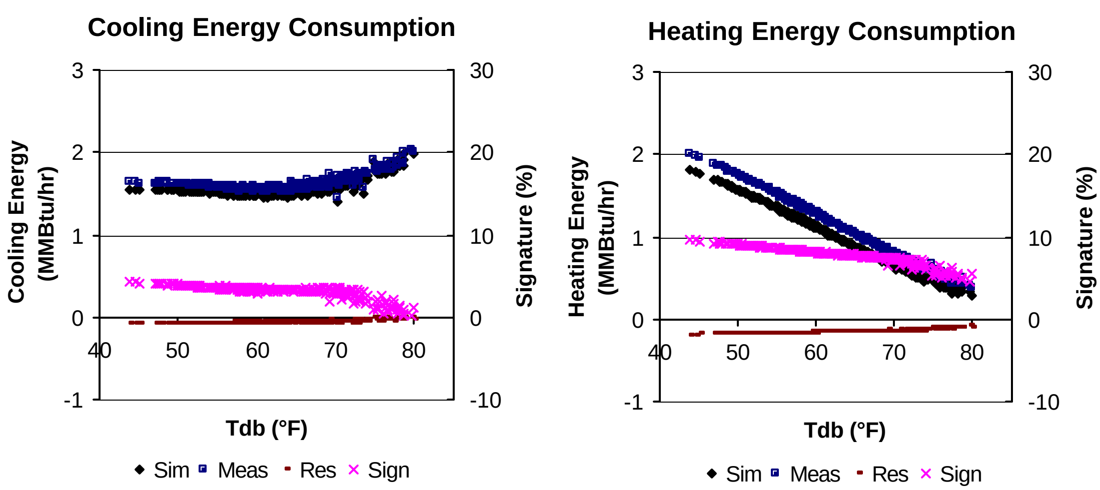
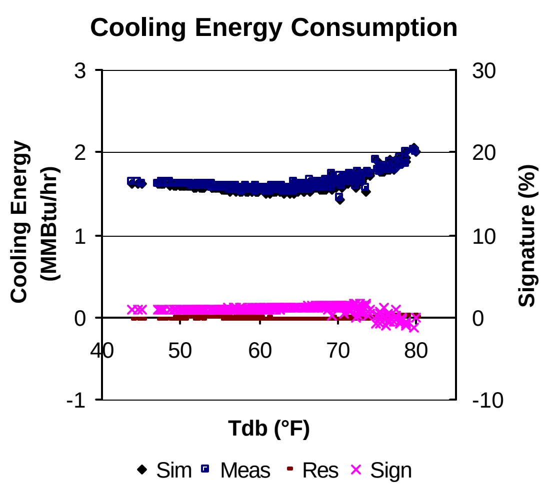


Figure 11. Simulation charts for Example 2 after the first iteration

Iteration 2. We see that we need to alter a calibration parameter so that both cooling and heating energy consumption increase over the entire range of outside air temperature, and the characteristic signatures for both cooling and heating should have negative slopes. Examining the characteristic signatures of Appendix E-1, we see that decreasing the cold deck temperature, increasing the supply air, or increasing the floor area all have these general characteristics. We note that increasing the floor area had a fairly large cooling characteristic signature at high temperatures, while the cooling calibration signature of Figure 11 is near zero at high temperatures, so we consider only cold deck temperature or supply air flow rate at this point. This is often true - the calibration signatures will not suggest a single option, but will point toward a small number of options. It is relatively easy to measure cold deck temperatures, so that would be a logical step at this point if one has access to the building. In this illustrative example, we chose to decrease the cold deck temperature because its cooling characteristic signature reaches zero at high temperatures.

It was not possible to bring both cooling and heating calibration signatures to zero by decreasing the cold deck temperature, but we found that when the cold deck temperature was decreased from 55 to 54 °F, the cooling RMSE dropped considerably from 0.07 to 0.02 MMBtu/hr. Both cooling and heating calibration signatures dropped over almost the entire range of outdoor temperatures as shown in Figure 12. The heating RMSE decreased from 0.16 to 0.12 MMBtu/h.



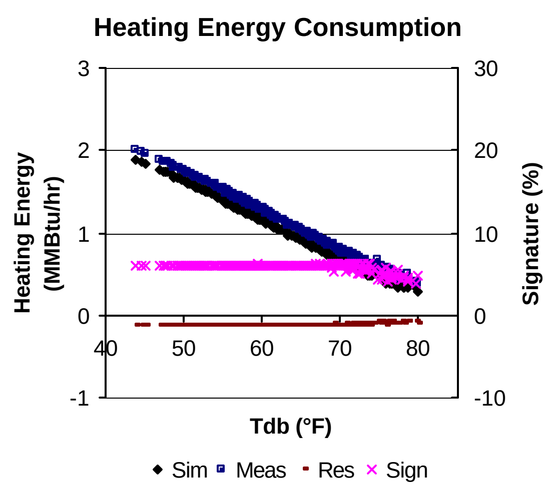


Figure 12. Simulation charts for Example 2 after iteration 2

Iteration 3. The calibration signatures are now both positive, but the heating signature is considerably larger than the cooling signature. None of the characteristic signatures match these characteristics, but room temperature characteristic signatures are both positive at low temperatures and the heating characteristic signature is twice as large as that of cooling. This calibration step will target the low temperature range assuming that the calibration signatures of Figure 12 require a set of combined characteristic signatures. In the characteristic signature, increasing the room temperature from 73 °F to 74 °F caused energy use to increase by 2% and 4% at low temperatures respectively for cooling and heating, while the calibration signatures are at 1% and 6% at low temperatures respectively for cooling and heating. This suggests that increasing room temperature by about 0.5 °F should bring the cooling calibration signature to zero at low temperatures, and increasing it by 1.5 °F should bring the heating calibration signature to zero at low temperature. It was decided to increase room temperature by only 0.5 °F to avoid too much effect on the high temperature side. The room temperature setpoint was therefore increased from 73 °F to 73.5 °F. Figure 13 shows simulation charts after this change. As expected, the cooling calibration signature has approached zero at low temperatures, but the cooling RMSE has actually increased slightly from 0.02 to 0.03 MMBtu/hr due to the slight increase at high temperatures. The heating RMSE has decreased slightly from 0.12 to 0.11 MMBtu/hr.

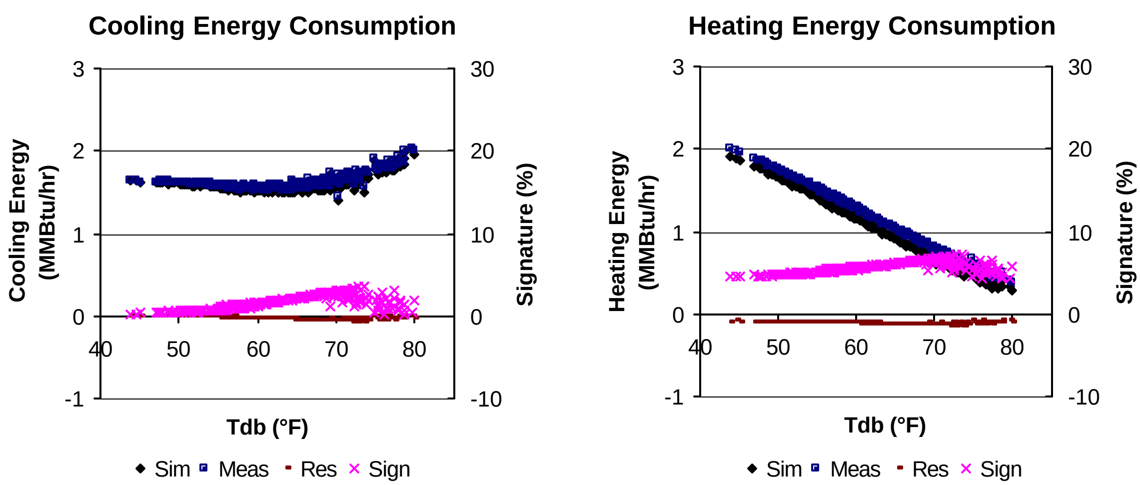


Figure 13. Simulation charts for Example 2 after iteration 3

Iteration 4. We now have peaks in the middle range of high temperatures in both the cooling and heating calibration signatures. Examination of the characteristic signatures of Appendix E-1 indicates that the hot deck temperature characteristic signatures have a similar trend. We found out that increasing the hot deck temperature to remove the peaks caused the RMSE to decrease for heating and increase for cooling, so both RMSE values were summed and a minimum value was sought. The best result was obtained by increasing the hot deck temperature by 2 °F. The heating RMSE dropped sharply from 0.11 MMBtu/hr to 0.04 MMBtu/hr and the cooling RMSE increased slightly from 0.03 to 0.05 MMBtu/hr. After this alteration, the peaks have been removed as shown in Figure 14.

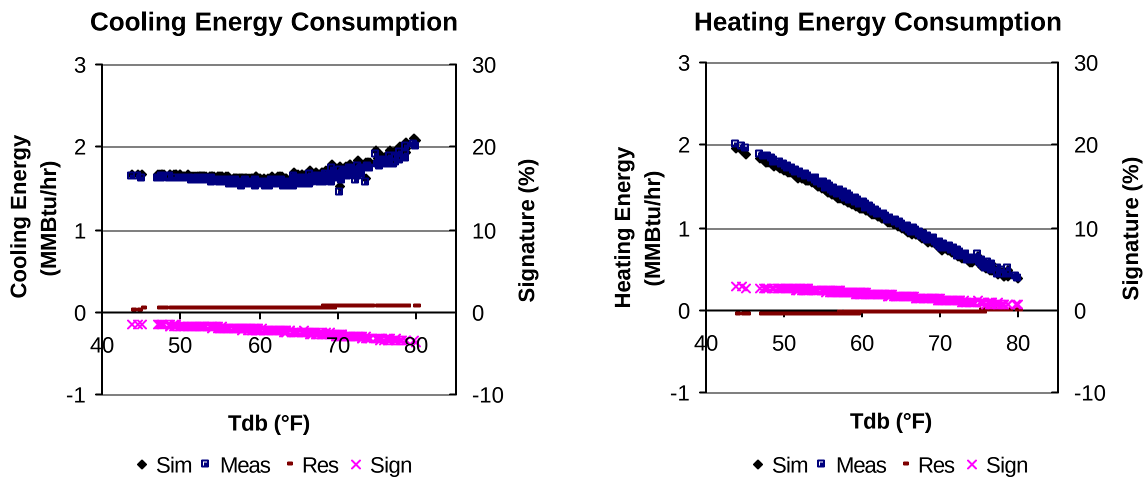


Figure 14. Simulation charts for Example 2 after iteration 4

Iteration 5. The calibration signature for cooling is now negative with a negative slope while the heating signature is positive with a negative slope. Alternatively, we can say that cooling energy consumption needs to be decreased, and heating energy consumption increased over the entire temperature range. The change should tend to zero at lower temperatures for cooling consumption, and at higher temperatures for heating consumption. Examining the signatures of Appendix E-1 shows that only a decrease in internal gain level has a similar set of signatures. In this set of signatures, a decrease of 0.4 W/ft^2 in internal gains caused maximum changes of -9% and 7% respectively for cooling and heating, while the calibration signatures reach -4% and 3% respectively for cooling and heating. This suggests that internal gains have to be decreased by about 0.15 to 0.2 W/ft^2. Different values were tested and the best result was obtained by decreasing internal gains from so 0.8 to 0.6 W/ft^2. It provided an extremely good match as shown in Figure 15. The calibration signatures have dropped to near zero over the whole range of temperatures, and the RMS errors are only 0.003 and 0.001 MMBtu/hr respectively for cooling and heating energy consumption. The simulation model is now calibrated.

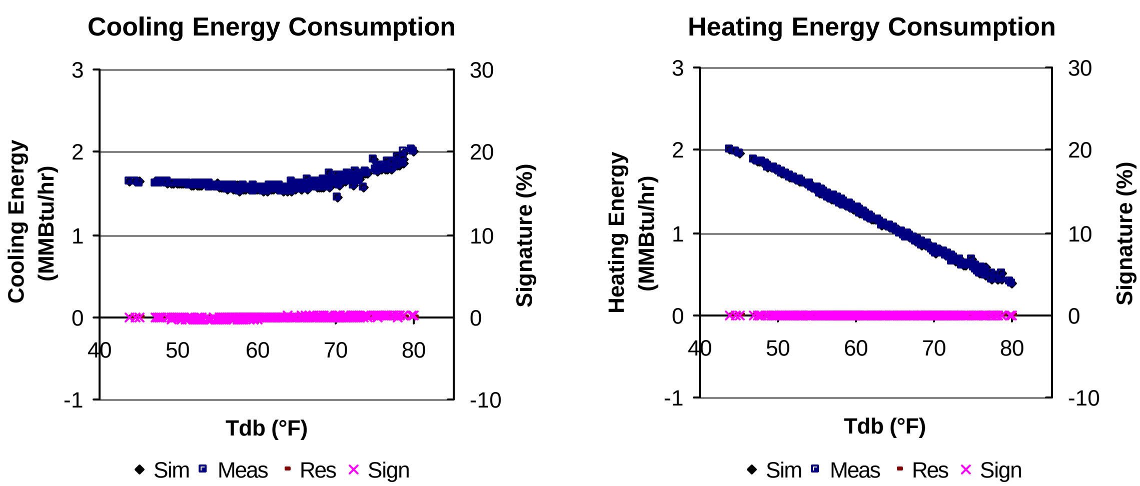


Figure 15. Calibrated simulation for Example 2

In this example, the generation of the original simulation the provided the "measured" data and the calibration process were conducted by two people. This was done to provide more realistic calibration conditions where the answer was not known by the one performing the calibration. The alterations made to generate the uncalibrated simulation and those made to calibrate the system are compared in Table 2.

Table 2. Comparison of calibration alterations with "real" errors

Input parameter	Model calibration	"Measured" Value
Outside air flow rate	0.1 → 0.14 cfm/ft^2	0.14 cfm/ft^2
Cold deck Temperature	55 → 54 °F	53.6 °F
Room Temperature	73 → 73.5 °F	73 °F
Hot deck Temperature	110 → 112 °F at T_{OA}=40 °F 80 → 82 °F at T_{OA}=70 °F 70 → 72 °F at T_{OA}=100 °F	111.5 °F at T_{OA}=40 °F 81.5 °F at T_{OA}=70 °F 71.5 °F at T_{OA}=100 °F
Internal heat gain	0.8 → 0.6 W/ft^2	0.55 W/ft^2

We notice that the changes made to input parameters to calibrate the model are close to those needed to correct the errors that were intentionally introduced to simulate the real building. Temperature differences were 0.5 °F or less, which is comparable to measurement accuracy.

Note that step 9 (hourly fine tuning) of the calibration procedure was not used in these examples. This step is rather helpful when calibrating to real data, which typically produces somewhat more scatter in the results than shown in these examples that used "measured" data generated by a simulation program. The case studies presented in the next section show the use of this final calibration step in real buildings.

IV. CASE STUDIES

This section describes two additional examples, using data from real buildings rather than simulations. These examples show that in real buildings, issues such as lack of sufficient measured data, operational changes, complex occupancy schedules, and multiplicity of systems can make the calibration process somewhat more complicated, but that the characteristic calibration signatures method still allowed the analyst to define a believable simulation with minimal effort.

The first building is located in Oakland, CA and the second in College Station, TX. In the second example, characteristic signatures were built using the building's own simulation since the published generic signatures in this manual correspond to a different climate. Appendix G shows how to create one's own characteristic signatures.

1. Case Study 1: Dalziel Building, Oakland, CA.

The Oakland Administration Building was constructed in 1998. It consists of two separate buildings, the Dalziel Building and the Wilson Building, with a combined gross area of 450,000 ft^2 and a relatively low whole building energy use of 50 $kBtu/ft^2/yr$ (Motegi et al, 2002).

The objective of this case study was to calibrate the simulation of cooling and heating energy consumption for Dalziel. This building, shown in Figure 16, has six floors with an estimated conditioned floor area of about 230,000 ft^2. The main HVAC system is a Single Duct Variable Air Volume (SDVAV) system with hot water reheat. Two 500-ton chillers, located in Dalziel, serve the main air handlers in both buildings, while each building has its own hot water boilers.

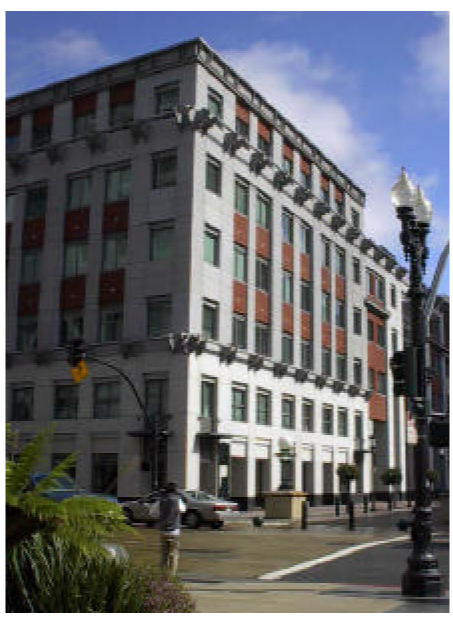


Figure 16. Picture of the Dalziel Building

Step 1. The major difficulty encountered in calibrating the Dalziel Building was frequent changes in the operating schedule of the building systems. In the interest of avoiding this issue, this case study considers only a 3-month period when the schedule was consistent, i.e. March 5 to June 2, 2000.

Step 2. AirModel was used for the simulation. The main input parameters for the initial simulation are shown in Table 3. They were taken or calculated from a report on the Oakland Administration Building (Eley Associates, 2001), as well as a set of files that includes measured data and input and output files from an earlier DOE-2 simulation provided by Motegi (Motegi, 2002). These input parameters were considered to be representative of expected operation of the building. Monthly solar gains were calculated using the Klein-Theilacker method (Duffie and Beckman, 1991). The months of December and July were established as having respectively the minimum and maximum solar gains. These two months were therefore used as the maximum and minimum solar gain inputs as required by AirModel as shown in Table 3. AirModel approximates solar gains as a linear function of outside air temperature (Knebel, 1983).

Table 3. Initial simulation parameters for case study 1

Parameter	**Value**
Conditioned floor area	231,557 ft^2
Interior zone ratio	0.2
Occupied period	6 am to 6 pm on weekdays only
Exterior wall and roof area	91.982 ft^2
Average exterior wall and roof U-value	0.073 Btu/ft^2.hr.°F
Window area	19,339 ft^2
Window U-value	0.34 Btu/ft^2.hr.°F
Room temperature setpoint T_{room}	72 °F
Minimum air flow rate	0.34 cfm/ft^2
Outside air flow rate	0.28 cfm/ft^2
Economizer range	40 - 70 °F
Average internal heat gain Q_{int}	1.8 W/ft^2
Solar gains	0.078 MMBtu/h at 42 °F, and 0.138 MMBtu/h at 88 °F
Air infiltration	None
Average occupancy	356 ft^2/person
Difference between return and room air temperatures	2 °F
Cold deck temperature T_c	64 °F
Preheat location	Outside air
Preheat temperature T_{ph} schedule	45 °F for T_{OA}<45 °F

Site measured weather data was used for the simulation. Figure 17 shows daily average dry-bulb temperature variations over the simulation period, and daily average relative humidity versus daily average dry-bulb temperature.

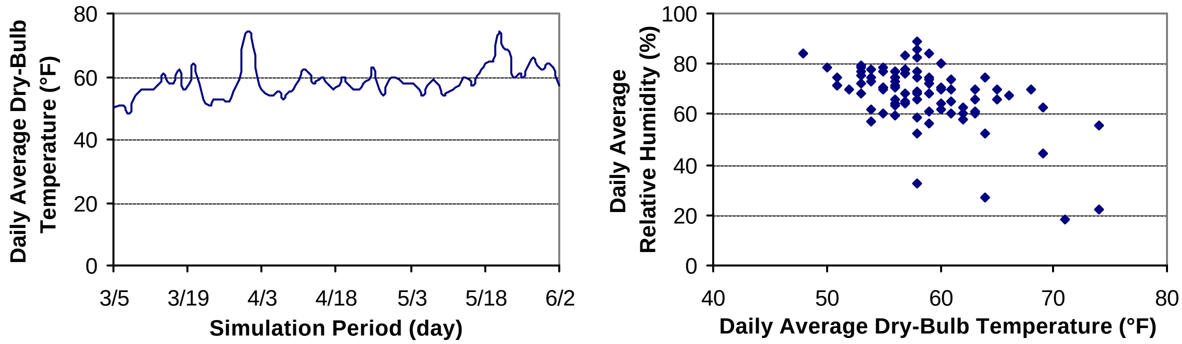


Figure 17. Weather conditions for the simulation period

Step 3. Daily average values were used for this simulation. In the authors' experience, using daily averages helps eliminate dynamic effects and reduce the scatter. The major difficulty was the small number of cooling data points. The number of hourly cooling data points was very small because chillers were turned off whenever the ambient temperature was less than 65°F; a large number of hourly measurements were also missing, so a number of days with insufficient hourly data were eliminated. In the absence of reliable cooling data, a model was created for cooling energy consumption using measured data from the period between June 5 and August 7, 2001, for which considerably more daily average cooling energy consumption (Q_{cool}) data points could be generated. The 3-parameter change point linear regression model of cooling consumption generated from this data was:

$$Q_{cool}\ (\text{MMBtu/hr}) = 0 \qquad \text{for } T_{db}\ (°F) < 59.63\ °F$$
$$= 0.0737\ T_{db}\ (°F) - 4.3949 \qquad \text{for } T_{db}\ (°F) \geq 59.63\ °F$$

Step 4. The RMS errors for the initial simulation were 0.13 and 0.36 MMBtu/hr respectively for cooling and heating energy consumption.

Step 5. Cooling and heating simulation charts for all calibration steps are illustrated in Figures 18 to 24 and in Figure 29. Figure 18 shows the initial simulation and Figure 29 shows the calibrated simulation. Each of these figures consists of four charts. The two charts on the left hand side are cooling charts and the two charts on the right hand side are heating charts. The upper ones show simulated (sim) and measured (meas) daily average energy consumption, as well as residuals (res) as defined in equation 2. The lower graphs show calibration signatures as defined in equation 1. The purpose of the solid line in the calibration signatures is to reveal the trend of the scattered data points, which makes it easier to compare the calibration signature to characteristic signatures. The trend line is a moving average of 6 points for cooling and 9 points for heating. Groups of an equal number of points have been used rather than temperature bins because data points were not distributed uniformly over the temperature range, and more points were used per group for heating than for cooling because there were considerably more heating than cooling data points.

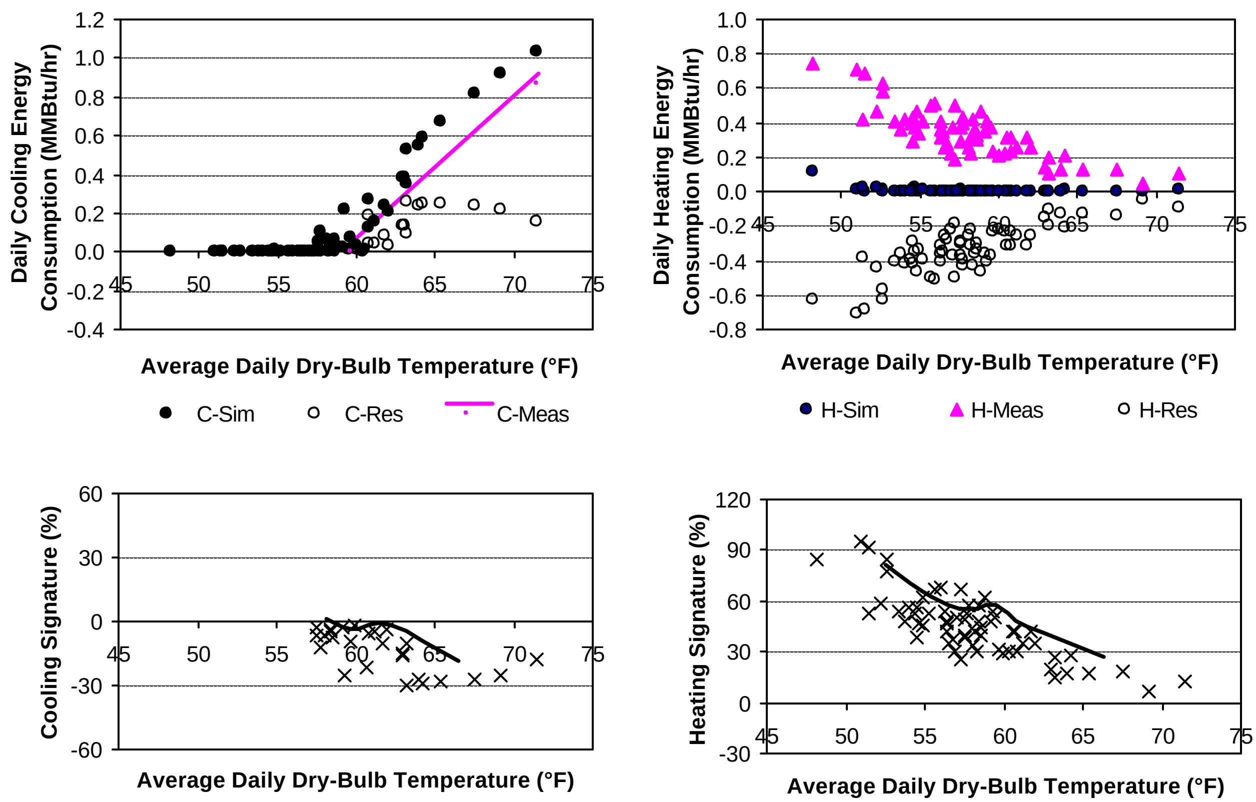


Figure 18. Initial simulation charts for case study 1

Step 6. After running the initial simulation, the major remark is that heating energy consumption is simulated to be zero, while the cooling simulation signature is relatively small. The objective of the first input change should be to produce heating energy consumption over the entire temperature range. The characteristic signatures in Appendix D-3, corresponding to SDVAV systems in Oakland, will be used for this case study. Examining these characteristic signatures, we notice that decreasing the cold deck temperature, increasing the minimum air flow rate, increasing the floor area, decreasing internal gains or increasing room temperature would cause heating to increase uniformly over the entire temperature range. Since the objective of this input change is to increase heating consumption as much as possible, the parameter to be altered for Iteration 1 will be chosen as the most sensitive among those mentioned above. The minimum air flow rate seems to be the most sensitive, since a decrease of as little as 0.03 cfm/ft^2 caused heating energy use to decrease by about 6% over the entire temperature range.

Step 7. The minimum air flow rate characteristic signature for heating is negative, while the heating calibration signature is positive, so the input parameter should be altered in the opposite sense, i.e. increased. The minimum air flow rate was increased to 0.8 cfm/ft^2.

Step 8. Figure 19 shows simulation charts after this change. The heating RMSE has decreased considerably from 0.36 to 0.28 MMBtu/hr. We notice that the effect of increasing the minimum air flow rate was more pronounced in the lower temperature range, while there was not much effect at higher temperatures, which explains why the cooling RMSE remained at 0.13 MMBtu/hr as there is no cooling energy consumption at low temperatures.

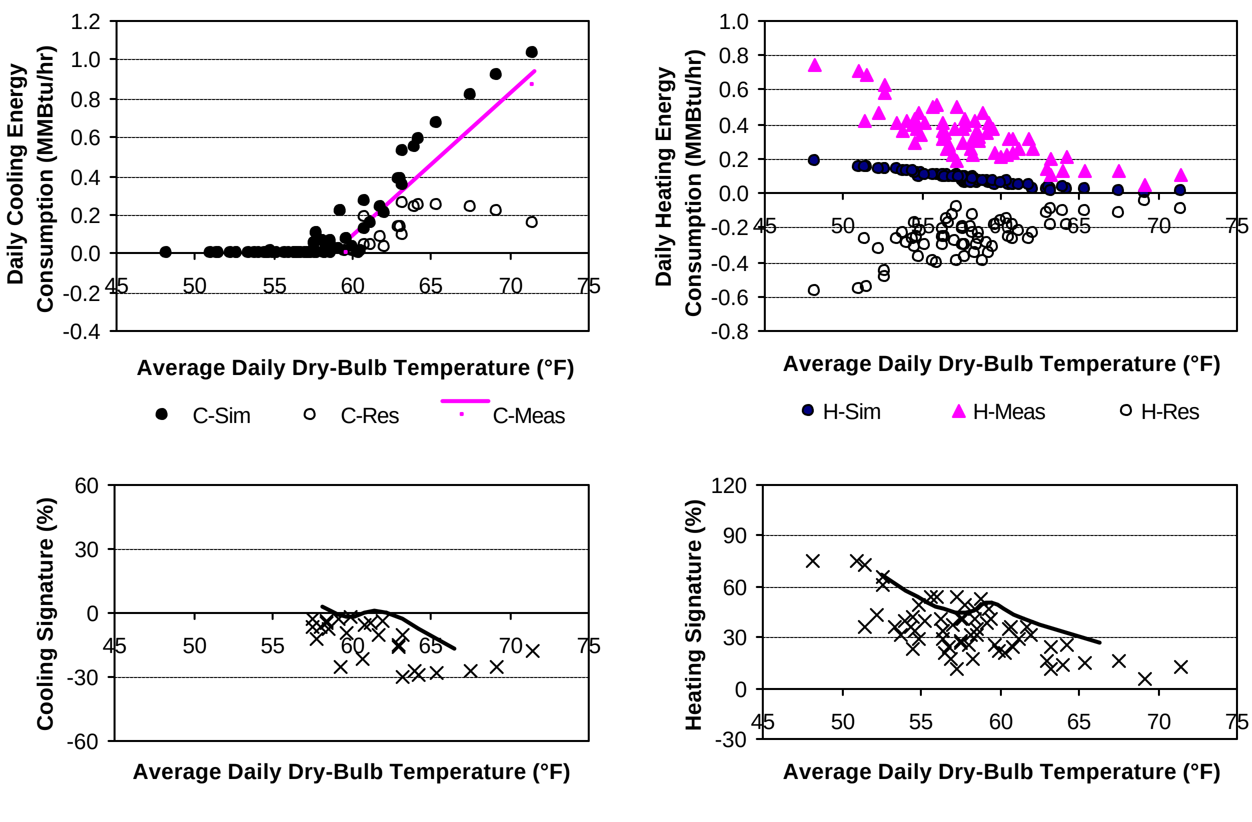


Figure 19. Cooling and heating simulation charts after the first iteration

Iteration 2. The calibration signature was considerably decreased for heating in Iteration 1. However, it still remains as large as 75% at low temperatures, while the cooling simulation signature is within -30%. This calibration step will focus again on heating energy consumption. Examining the characteristic signatures in Appendix D-3, we notice that decreasing the internal gain should decrease the heating calibration signature over the total temperature range without much effect on cooling. It should even decrease the cooling calibration signature at high temperatures since the cooling characteristic signature also has a negative slope at high temperatures. The best result was obtained by decreasing the internal heat gain from 1.8 to 1.25 W/ft^2. Figure 20 shows simulation charts after this change. The RMS errors have decreased from 0.13 to 0.11 MMBtu/hr for cooling and from 0.28 to 0.12 MMBtu/hr for heating.

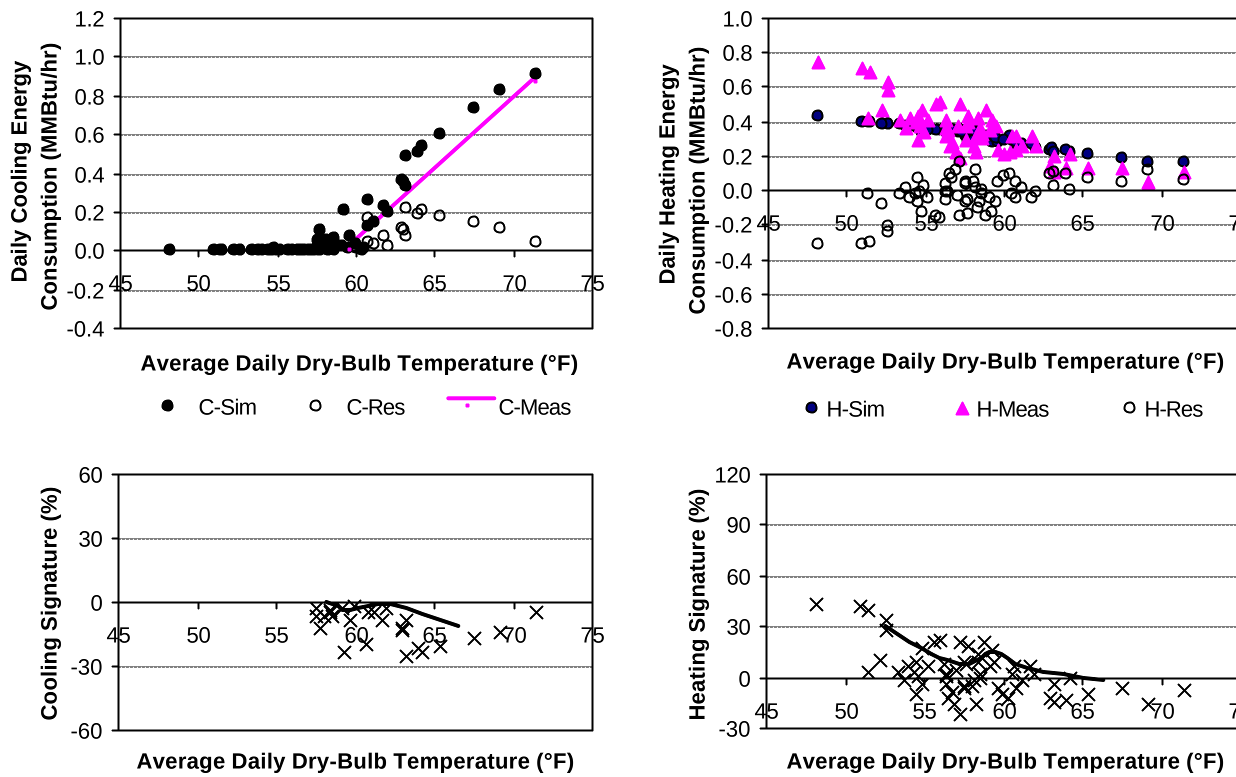


Figure 20. Cooling and heating simulation charts after iteration 2

Iteration 3. Both cooling and heating RMS errors have decreased after Iteration 2. But, the heating calibration signature still has a steep negative slope at low temperatures. Examining the characteristic signatures in Appendix D-3, we notice that the heating characteristic signature for outside air is comparable to the heating calibration signature in Figure 20. Therefore, increasing the outside air flow rate should neutralize or reduce the negative slope at low temperatures in the heating calibration signature. The calibration and characteristic signatures for cooling do not match. In order to reduce the effect on the cooling calibration signatures, the outside air flow rate was increased to partially neutralize the negative slope at low temperatures for heating and make it uniform with the rest of the signature. The outside air flow rate was increased from 0.28 to 0.42 cfm/ft^2. Figure 21 shows simulation charts after this alteration. The RMSE has decreased from 0.12 to 0.10 MMBtu/hr for heating and increased slightly from 0.11 to 0.12 MMBtu/hr for cooling.

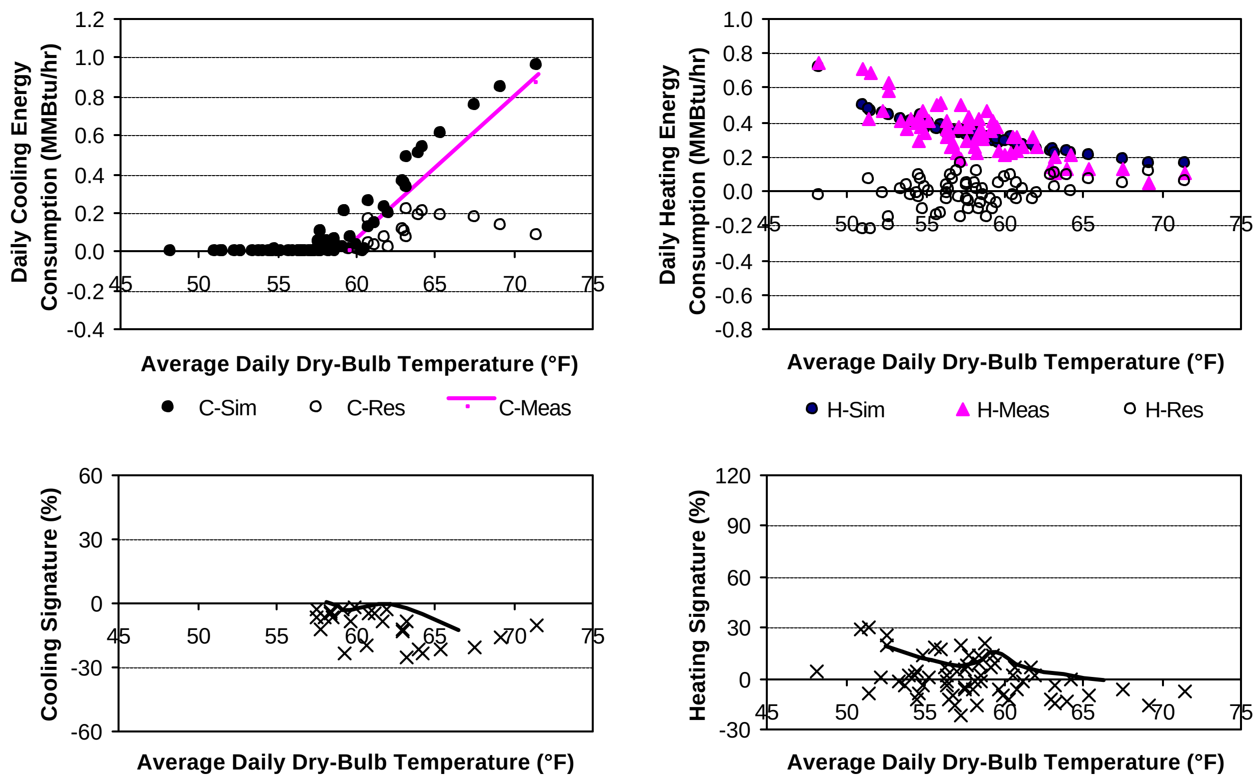


Figure 21. Cooling and heating simulation charts after iteration 3

Iteration 4. Now that the heating simulation signature has been reduced to reasonable values, the purpose of this calibration step is to reduce the cooling simulation signature over the entire temperature range. The cooling calibration signature in Figure 21 is negative over the total temperature range. It is almost constant at lower temperatures and has a negative slope at high temperatures. Examining the characteristic signatures in Appendix D-3, we notice that the cooling characteristic signatures for the cold deck temperature (T_c) and the room temperature setpoint (T_{room}) have similar trends and are both positive. Therefore, decreasing the cold deck temperature and/or increasing the room temperature setpoint should neutralize the negative slope at high temperatures, but would increase cooling energy consumption at lower temperatures instead of decreasing it. Similarly, increasing the cold deck temperature and/or decreasing the room temperature setpoint should decrease cooling energy consumption, but would make the negative slope at high temperatures even steeper. In order to decreasing cooling energy consumption and at the same time neutralize the negative slope at high temperatures, both the cold deck temperature and the room temperature setpoint have to be altered, one in the same direction as in the characteristic signature and one in the opposite direction, i.e. both increased or decreased. The best result was obtained by increasing the cold deck temperature from 64 °F to 66 °F and the room temperature setpoint from 72 °F to 73.5 °F. Figure 22 shows simulation charts after this iteration. The RMSE has decreased considerably for cooling from 0.12 to 0.06 MMBtu/hr. It has decreased slightly for heating from 0.10 to 0.09 MMBtu/hr.

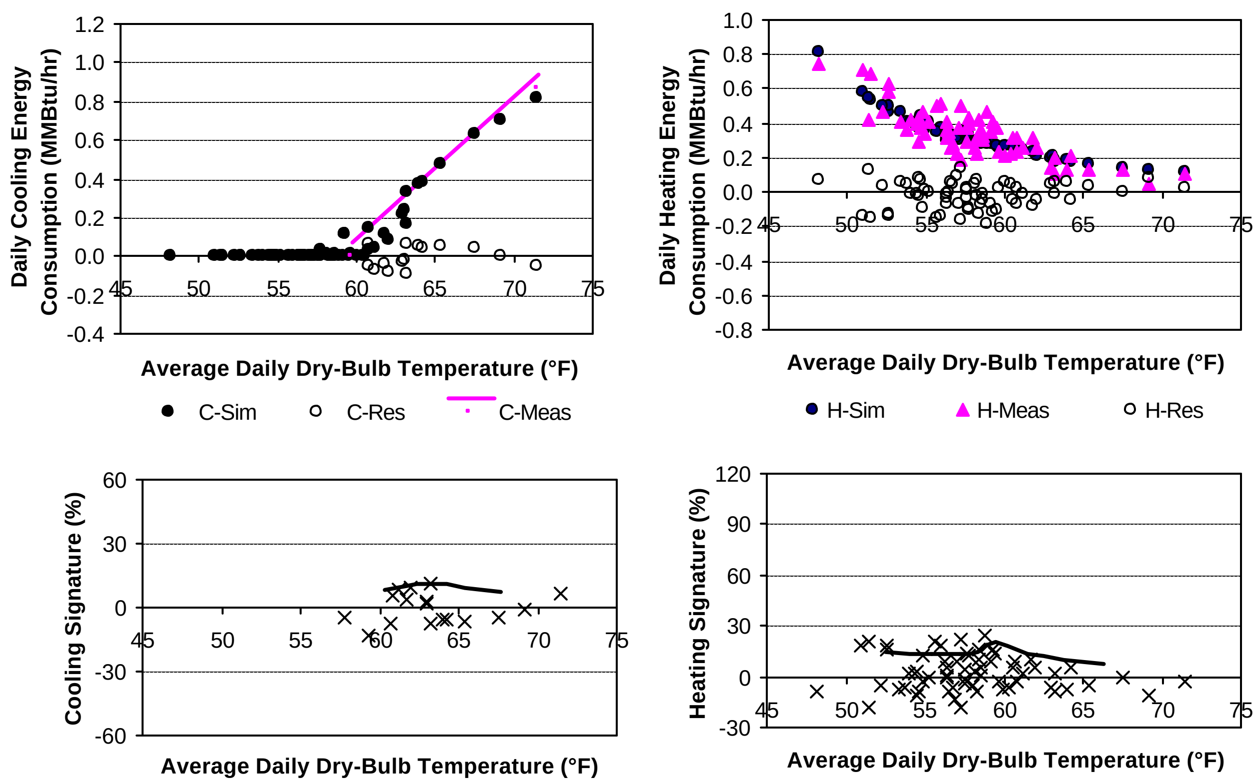


Figure 22. Cooling and heating simulation charts after iteration 4

Iteration 5. Both cooling and heating RMS errors have decreased to reasonable values in the previous simulation. But, we notice that the heating calibration signature in Figure 22 still has a slightly negative slope. Examining Appendix D-3, we notice that the heating characteristic signature for the envelope U-value has a constant positive slope. This characteristic signature was obtained by decreasing the envelope U-value. Therefore, the envelope U-value has to be increased in this calibration step to match the negative slope of the heating calibration signature. The best result was obtained by increasing the U-value by 20%. Consequently the exterior wall and window U-values were increased respectively from 0.073 to 0.088 Btu/ ft^2.hr.°F and from 0.34 to 0.41 Btu/ ft^2.hr.°F. Figure 23 shows simulation charts after this iteration. The RMSE has slightly decreased for heating from 0.09 to 0.08 MMBtu/hr and remained at 0.06 MMBtu/hr for cooling.

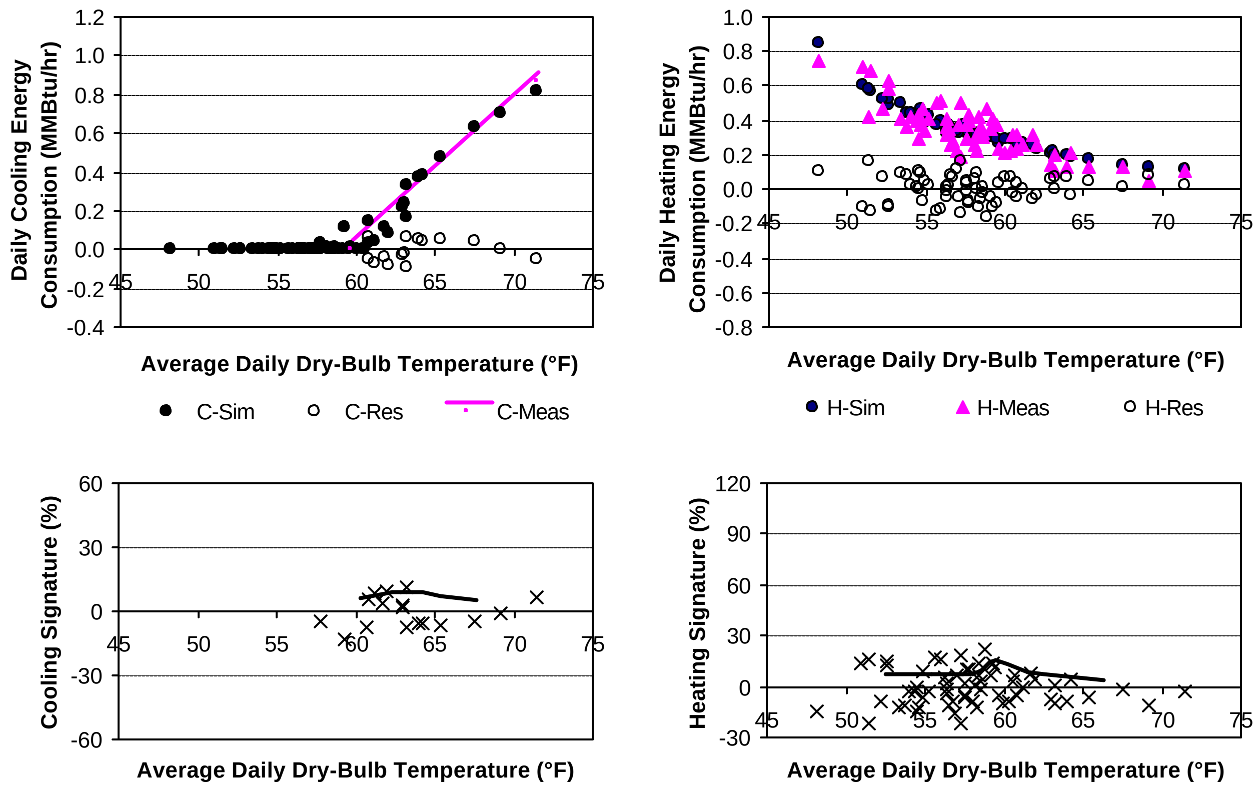


Figure 23. Cooling and heating simulation charts after iteration 5

Step 9. The objective is to fine-tune the calibration by calibrating the simulation of hourly data. This is achieved by introducing the daily internal gain profile, shown in the right hand side of figure 24, and calculated from the hourly variations of light and plug loads in the building, shown in the left hand side of figure 24. The daily internal gain profile was defined for each hour as the ratio of the internal gain to the maximum internal gain. It was calculated for weekdays only as there were no vacation periods and the HVAC system was shut off on weekends during the calibration period.

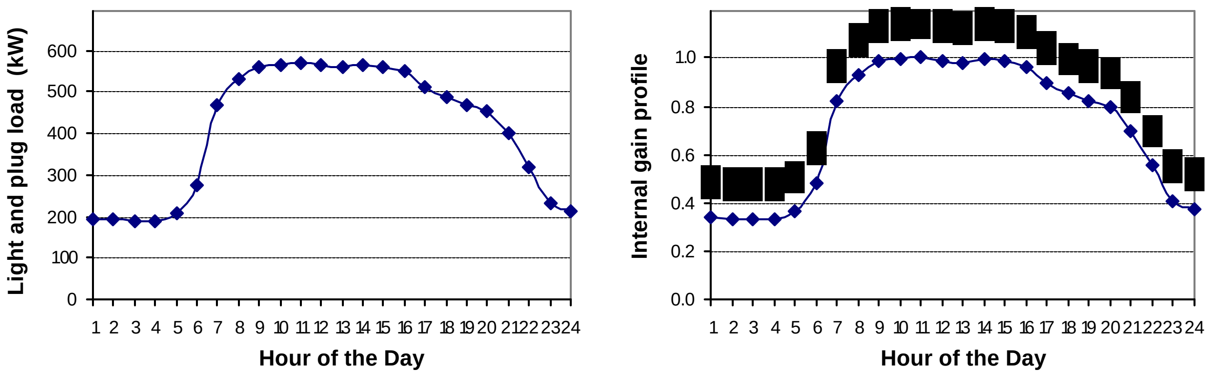


Figure 24. Hourly light & plug load (left) and deduced daily internal gain profile (right)

Therefore, instead of using an average heat gain of 1.25 W/ft^2 for each hour of the day, a maximum internal gain will be used along with the internal gain profile of figure 24. The only parameter that needs to be adjusted is the maximum internal gain. Different values were tested and the best result was obtained with 1.42 W/ft^2.

Figure 25 shows calibrated simulation charts. We notice on the heating calibration signature that the hourly calibration has reduced the negative slope at high temperatures. The heating RMSE has actually decreased from 0.08 to 0.07 MMBtu/hr while the cooling RMSE has remained at 0.06 MMBtu/hr.

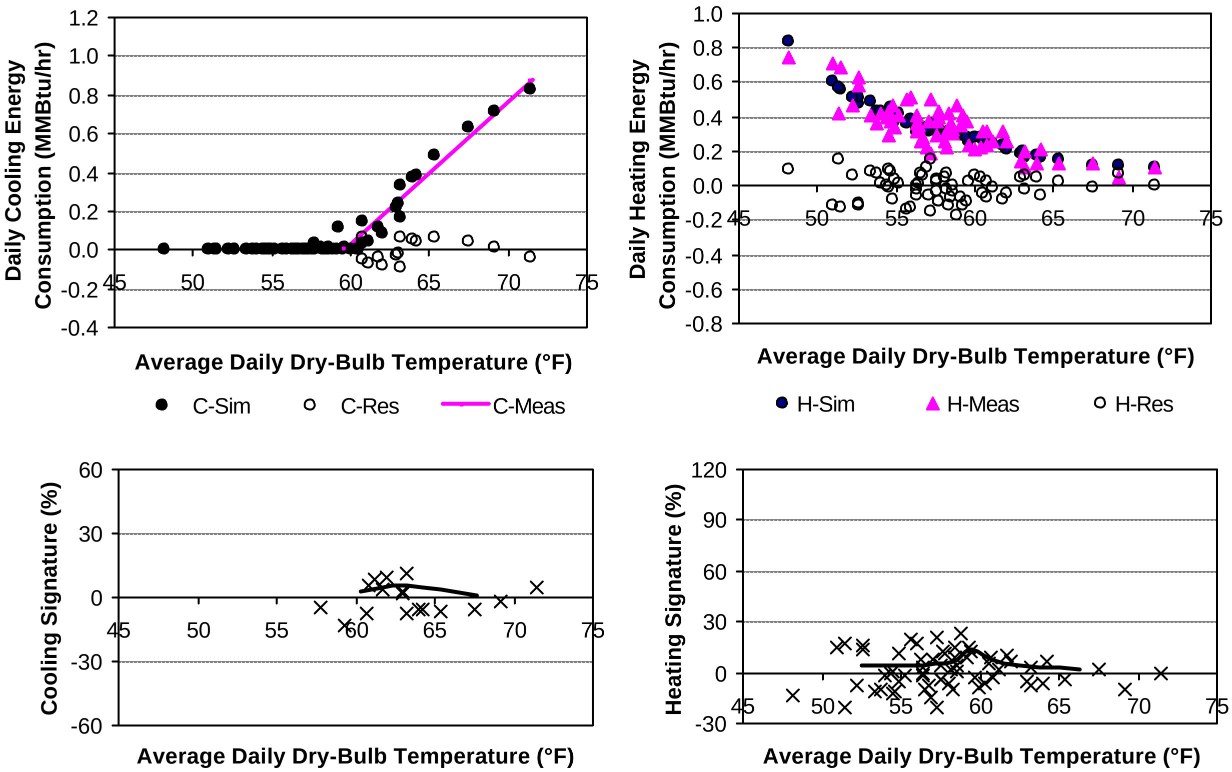


Figure 25. Calibrated simulation charts for case study 1

The bulge in the middle of the heating calibration signature is due to the way the temperature range was divided into small intervals of equal numbers of data points. It turned out that the bulge corresponded to an interval where most of the signature data points were higher than the neighboring data points. They would have cancelled out within a larger or shifted temperature interval.

Otherwise, the residuals are randomly scattered around zero and calibration signatures show no trend with temperature for both cooling and heating. The RMS errors have also been reduced to very small values, i.e. 0.06 and 0.07 MMBtu/hr respectively for cooling and heating. Table 4 shows a summary of the calibration steps. The mean Bias error (MBE) is shown for each calibration step for both cooling and heating. It has been reduced from 0.12 to 0.004 MMBtu/hr for cooling and from -0.33 to 0.005 MMBtu/hr for heating during the calibration process.

Table 4. Summary of calibration steps

Simulation parameter and alteration	Heating (MMBtu/hr)		Cooling (MMBtu/hr)	
	RMSE	**MBE**	**RMSE**	**MBE**
Initial simulation	0.36	-0.33	0.13	0.12
Minimum air flow rate: 0.34 → 0.8 cfm/ft^2	0.28	-0.25	0.13	0.12
Internal gain (average): 1.8 → 1.25 W/ft^2	0.12	-0.016	0.11	0.09
Outside air flow rate: 0.28 → 0.42 cfm/ft^2	0.10	0.003	0.12	0.10
Cold deck temperature: 64 → 66°F, and room temperature: 72 → 73.5°F	0.09	-0.009	0.06	0.004
Envelope U-value: Increased by 20% ◆ Exterior wall and roof: 0.073 → 0.088 Btu/ft^2.hr.°F ◆ Window: 0.34 → 0.41 Btu/ft^2.hr.°F	0.08	0.012	0.06	0.005
Hourly calibration ◆ Internal gain: 1.25 av. → 1.42 W/ft^2 max. ◆ Internal gain profile: Figure 24 (right)	0.07	0.005	0.06	0.004

We notice that the calibration process in this case study was rather focused on heating energy consumption, and that was due to the large heating RMSE in the initial simulation (0.36 MMBtu/hr compared to 0.13 MMBtu/hr for cooling). It took two calibration steps to bring it down to the level of the cooling RMSE. This is because reasonable alterations in input parameters produce limited changes in total energy consumption (expect for adding or removing an economizer as can be seen in Appendix D-3).

The calibrated simulation RMS errors were very low for this case study. But, simulation signature data points were quite high (± 10 % for cooling and ± 25 % for heating). This is due to the low energy consumption. In fact, the maximum daily average energy consumption was 0.8 MMBtu/hr for cooling and heating. For the sake of comparison, the maximum daily average energy consumption for a building with a comparable conditioned floor area in College Station, TX - namely the Zachry Engineering Center presented in the second case study - is 6.5 MMBtu/hr for cooling and 2.5 MMBtu/hr for heating. This consumption level would have produced signatures in the range of ± 1 % for cooling and ± 9 % for heating with the RMS errors of this case study.

2. Case Study 2: Zachry Engineering Center

Step 1. The Zachry Engineering Center (ZEC), shown in figure 26, is a Texas A&M University campus building. It is simulated in this case study to illustrate real building calibration using the proposed methodology. The building consists of four floors plus an unconditioned parking basement. It was constructed in the early 1970s and is a heavy structure with 6-inch concrete floors and insulated exterior walls made of pre-cast concrete and porcelain-plated steel panels. About 12% of the exterior wall area is covered with single-pane bronze-tinted glazing. The windows are recessed approximately 24 inches from the exterior walls, which provides some shading. Approximately 3,100 ft^2 of northeast-facing clerestory windows admit daylight into the core of the building. Measured energy consumption and weather data were retrieved from the Energy Systems Laboratory's database.

Figure 26. Zachry Engineering Center (ZEC)

Step 2. AirModel was used for this case study and the simulation was conducted using 1994 data. Daily average dry-bulb temperatures (T_{db}) for the simulation period are shown in the left hand chart of figure 27. The right hand chart shows relative humidity (RH) as a function of dry-bulb temperature.

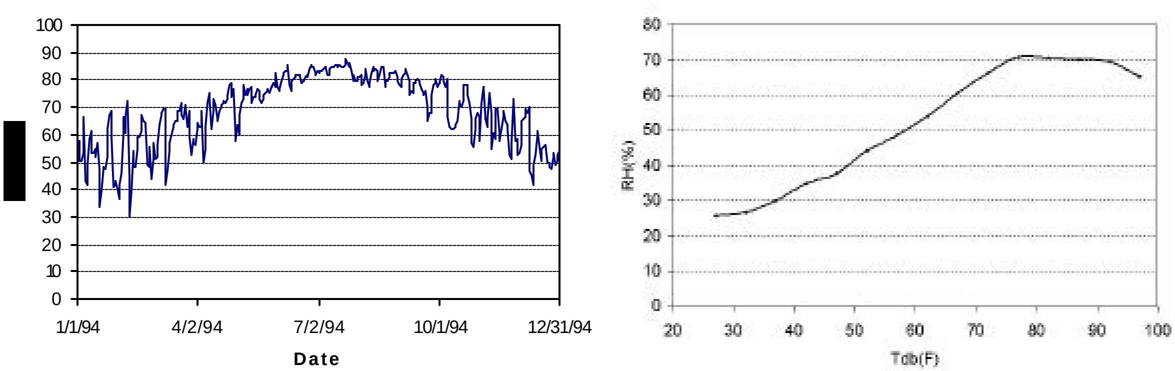


Figure 27. College Station, TX weather conditions for the simulation period

The input parameters used in the initial simulation are summarized in Table 5. They were measured, approximated or retrieved from multiple sources. As AirModel can accept a maximum of three vacation periods, so the longest vacation periods have been modeled and data during the others was eliminated.

Table 5. Initial simulation input parameters for ZEC case study

Parameter	**Value**
AHU type	DDVAV
Conditioned floor area	260,000 ft^2
Interior zone ratio	0.66
Occupied period	8 am to 6 pm
Vacation periods	Jan 4 to 16, May 15 to 29 and August 10 to 28
Exterior wall and roof area	115,040 ft^2
Average exterior wall and roof U-value	0.08 Btu/ft^2.hr.°F
Window area	25,308 ft^2
Window U-value	0.70 Btu/ft^2.hr.°F
Design room temperature	75 °F
Minimum air flow rate	0.5 cfm/ft^2
Outside air flow rate	0.2 cfm/ft^2
Economizer range	None
Average internal heat gain	3.1 W/ft^2
Solar gains (linear between defined points)	0.08 MMBtu/h at 20 °F, and 0.20 MMBtu/h at 110 °F
Average occupancy	180 ft^2/person
Difference between return and room air temperatures	2 °F
Cold deck temperature	55 °F
Hot deck temperature schedule (linear between defined points and constant outside lower and higher limits)	110 °F at T_{OA}=20 °F 90 °F at T_{OA}=42 °F 65 °F at T_{OA}=62 °F
Preheat location	Outside air

Step 3. The ESL database collects hourly energy consumption and weather data in 15-min intervals for this building. Therefore measured data had to be converted to hourly data for the simulation and then to daily data for the calibration.

Step 4. The residuals, the RMS errors and the calibration signatures were calculated for the initial simulation. The RMS errors were 15.4 and 7.0 MMBtu/day respectively for cooling and heating energy consumption.

Step 5. Figure 28 shows the initial simulation charts. The two charts on the left hand side are cooling charts and the two charts on the right hand side are heating charts. The upper ones show simulated (sim) and measured (meas) daily energy consumption, as well as the residuals (res) as defined in equation 2. The lower graphs show calibration signatures as defined in equation 1. The purpose of the solid line in the calibration signatures is to reveal the trend of the scattered data points, which makes it easier to compare the calibration signature to characteristic signatures.

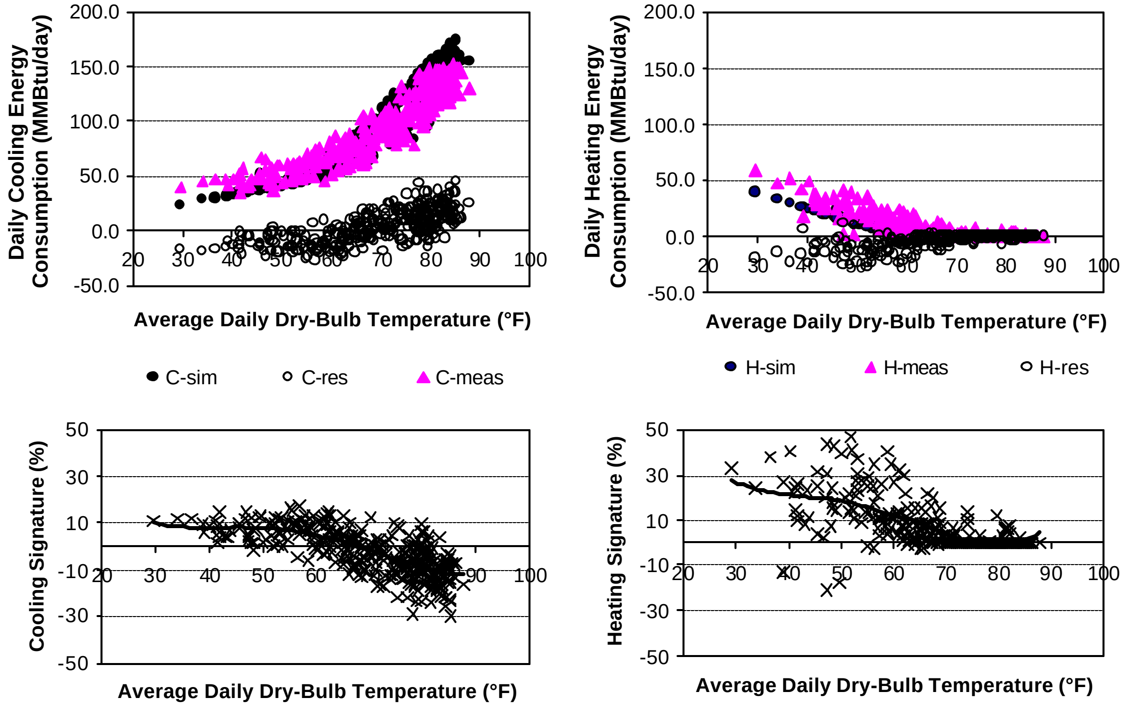


Figure 28. Initial simulation charts for case study 2

Step 6 Since College Station, TX weather is quite different from California weather, it was necessary to generate characteristic signatures for this building. This was done following the procedure described in appendix G. Based on the characteristics of this case study, the input parameters that were considered are the minimum air flow rate (V_{min}), internal heat gain (Q_{int}), outside air flow rate for the interior and exterior zones (respectively $V_{oa(int)}$ and $V_{oa(int)}$), room temperature setpoint (T_{room}), wall and windows U-values, hot deck temperature (T_h) and cold deck temperature (T_c). 5°F temperature bins were used to generate the characteristic signatures. Figure 29 shows the characteristic signatures generated for this case study. Parameter changes are shown at the top of each signature chart.

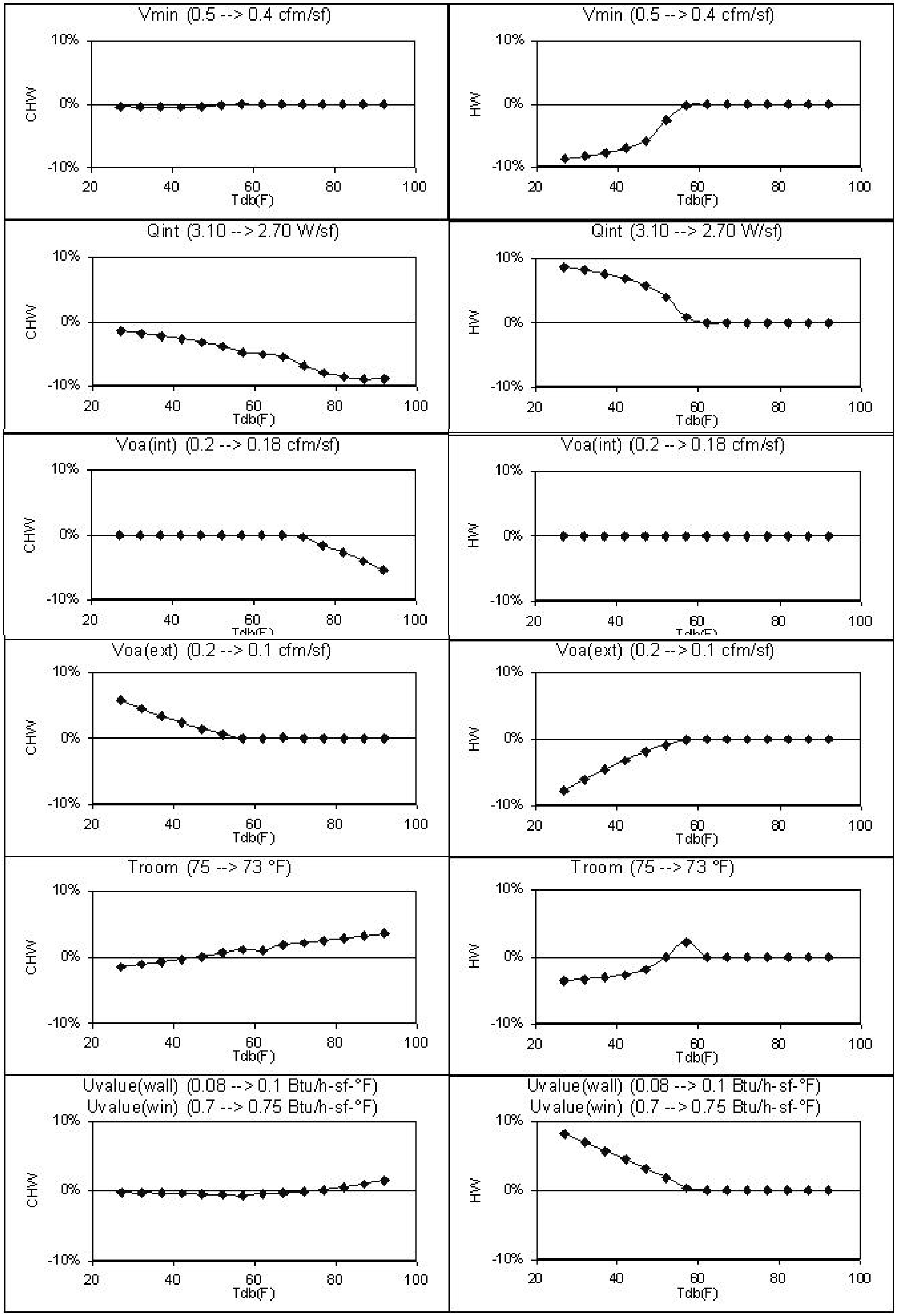


Figure 29. Characteristic signatures for Zachry building

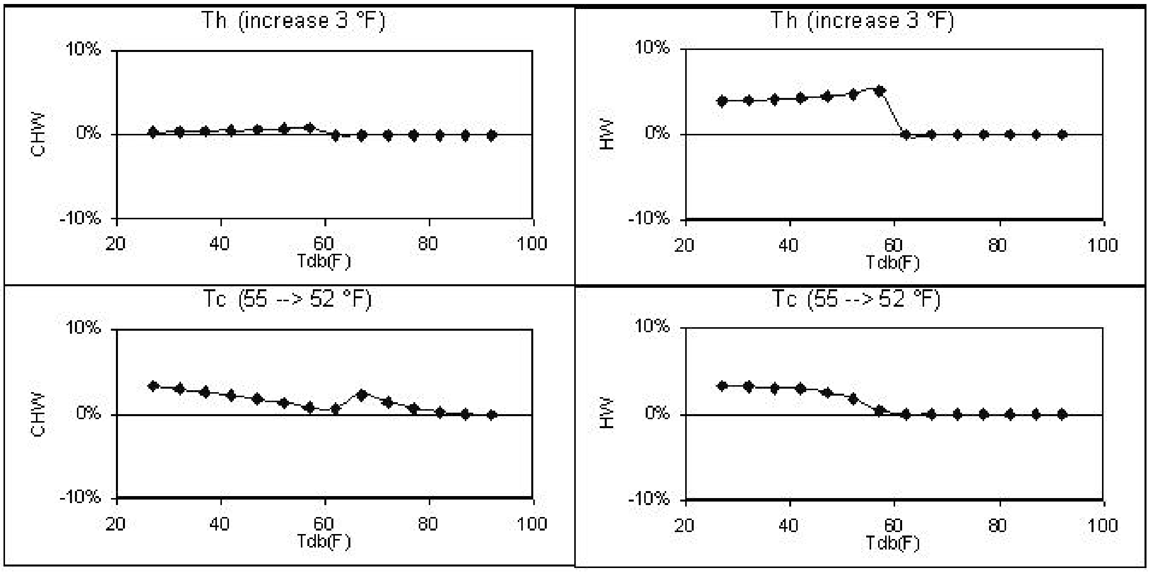


Figure 29. Characteristic signatures for Zachry building (continued)

Examining the calibration signatures in figure 28, we notice that cooling energy consumption needs to be increased by about 10% in the lower temperature range and decreased by about 10% in the higher temperature range. Heating energy consumption needs to be increased by about 30% in the lower temperature range. These calibration signatures can be matched by combining the characteristic signatures of figure 29 for increasing hot deck temperature, decreasing cold deck temperature and decreasing internal heat gain.

Step 7. To determine the input parameters that should be changed, and the amount of change, the magnitudes and patterns of the characteristic signatures should be compared with those of the cooling and heating calibration signatures. It appears that decreasing internal heat gain from 3.1 to 2.7 W/ft^2 (0.4 W/ft^2 as in the signature), increasing the hot deck temperature by 5 °F for the entire schedule (vs. 3 °F in the signature), and lowering the cold deck temperature by 3 °F may combine to increase hot water consumption increase by about 17% at low outside air temperatures. These parameter changes should also decrease the chilled water consumption when the outside air temperature is high. These changes would also increase chilled water (CHW) consumption when outside air temperature is low, but probably by only 5%. Thus we are still looking for another 5% CHW increase when outside air temperature is low and 13% hot water (HW) consumption increase. We therefore choose to decrease exterior zone outside air flow rate (from 0.2 to 0.1 cfm/ft^2) and increase wall and window U-values (from 0.08 to 0.1 and from 0.7 to 0.75 respectively). We must be careful to keep all parameter values physically reasonable. For example, a cold deck temperature below 50 °F is unlikely.

Step 8. The results of the first iteration are shown in figure 30. The RMSE values for CHW and HW decreased from 15.4 and 7.0 MMBtu/day to 12.0 and 5.6 MMBtu/day respectively. The MBE values for CHW and HW changed from 4.0 and -3.5 MMBtu/day to -7.5 and -2.4 MMBtu/day. The shape of the CHW calibration signature flattened significantly. However the HW calibration signature shows that HW consumption still needs to increase.

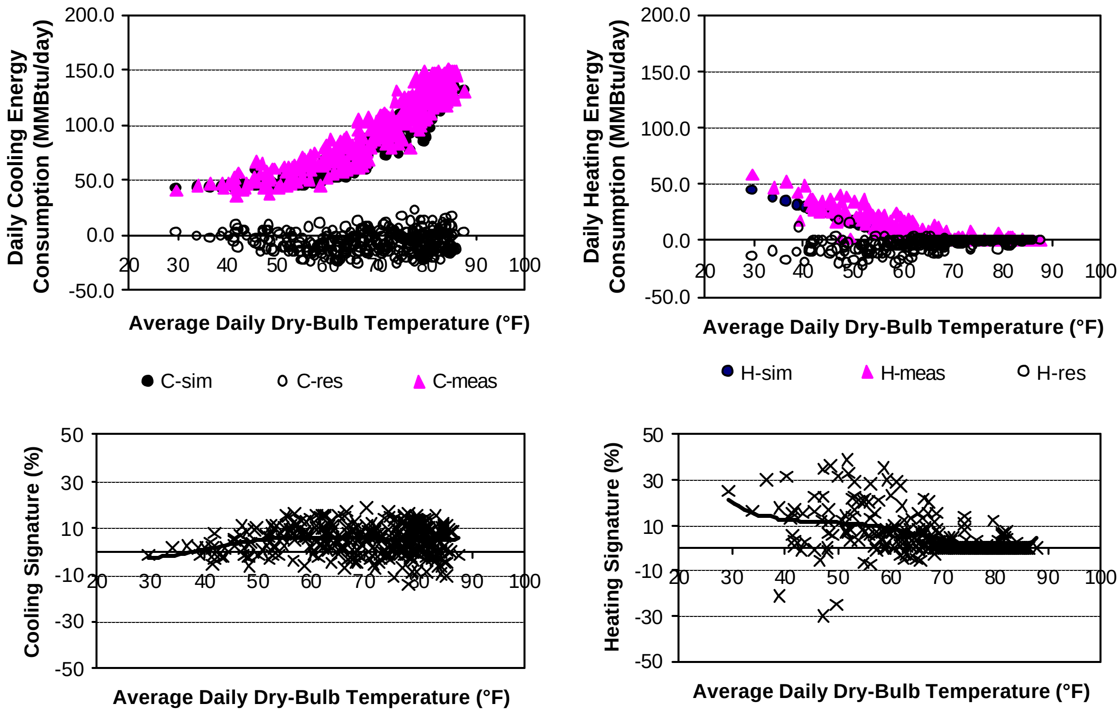


Figure 30. Cooling and heating simulation charts after the first alteration

Iteration 2. According to the calibration signature of figure 30, the CHW consumption need to increase by 7% when the outside air temperature is above 50 °F. The HW consumption needs to increase by 5-23% when the outside air temperature is lower than 70 °F. Examining the characteristic signatures indicates that changing internal heat gain and hot deck temperature may make both simulated CHW and HW close to the measured values. It was decided to increase internal heat gain from 2.7 to 3.0 W/ft^2, and modify the hot deck temperature schedule so it is 130 °F when outside air temperature is 20 °F or below, 105 °F when outside air is 42 °F, 90 °F when outside air is 50 °F, and 70 °F when outside air is 62 °F or above.

The results of the Iteration 2 are shown in figure 31. The RMSE for CHW and HW decreased from 12.0 and 5.6 MMBtu/day to 9.5 and 5.0 MMBtu/day respectively. The MBE of CHW and HW changed from -7.5 and -2.4 MMBtu/day to -0.5 and -1.8 MMBtu/day.

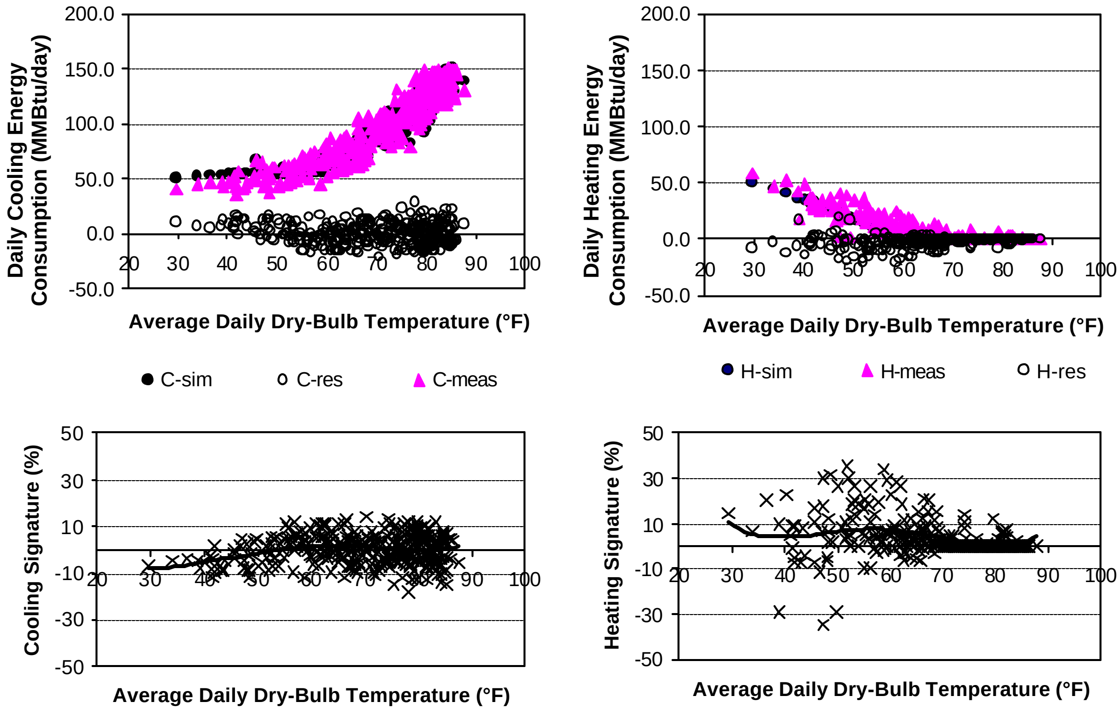


Figure 31. Cooling and heating simulation charts after iteration 2

Iteration 2 was successful in shifting the CHW and HW consumption upward. However the calibration signatures are still not uniformly close to zero.

Iteration 3. The CHW and HW signatures from iteration 2 show that during mild and hot weather conditions, the simulation model is well calibrated; however when the weather is cold, simulated CHW consumption is excessive and HW consumption is low. Based on the calibration signatures, it was decided to make the following changes. The exterior zone outside air flow rate was increased from 0.1 to 0.14 cfm/ft^2, window U-value was increased from 0.75 to 1.0 Btu/ft^2.hr.°F, and the hot deck temperature schedule modified to 95 °F when outside air temperature is 50 °F, 75 °F when outside air temperature is 62 °F, and 70 °F when outside air temperature is 85 °F or above.

Iteration 3 improved the calibration as shown in figure 32. The RMSE for CHW did not change from 9.5 MMBtu/day. However the CHW calibration signature pattern has been stabilized. The RMSE for HW decreased from 5.0 to 4.5 MMBtu/day. The MBE values for CHW and HW changed from -0.5 and -1.8 MMBtu/day to -1.0 and 0.0 MMBtu/day. There is still more room to improve the HW signature at low outside temperatures and improve the MBE for CHW.

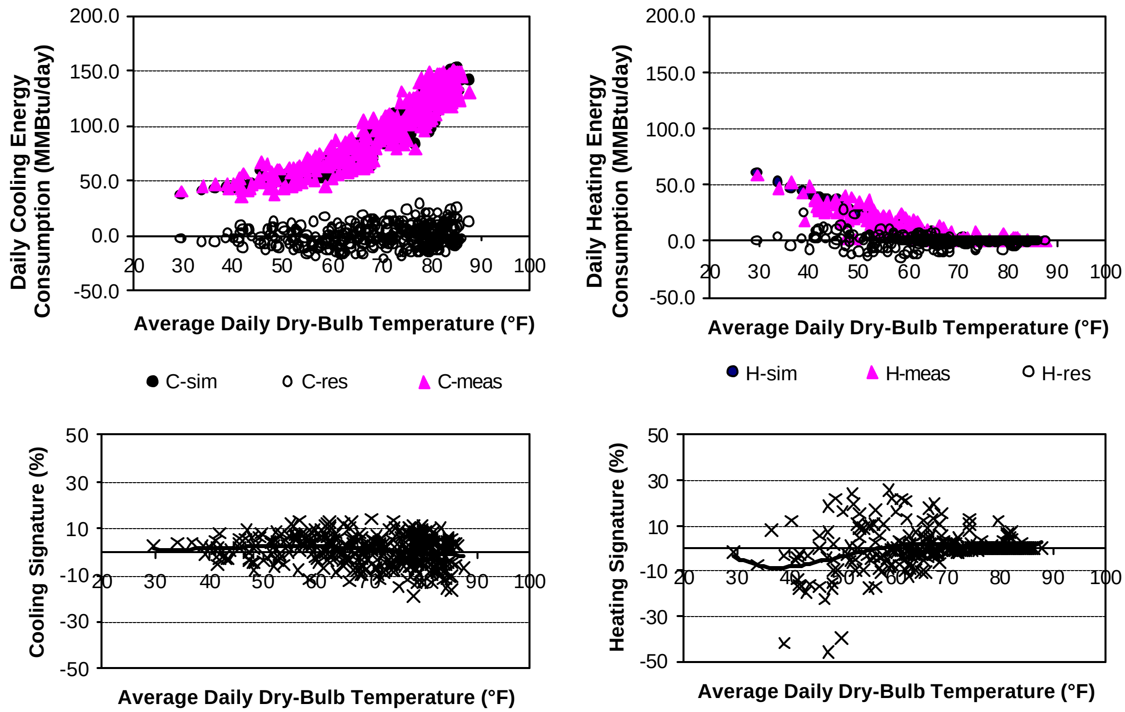


Figure 32. Cooling and heating simulation charts after iteration 3

Iteration 4. The HW calibration signature from Iteration 3 (figure 32) shows that for mild weather conditions, the simulation is well calibrated, but simulated cold weather HW consumption is too high. The HW characteristic signature for the U-value of the building is opposite the shape of the HW calibration signature. To lower the HW consumption for cold weather and fine tune the CHW, it was decided to change window U-value from 1.0 to 0.85 Btu/ft^2.hr.°F.

Iteration 4 (figure 33) improved the HW calibration signature and the RMSE values for CHW and HW decreased from 9.5 and 4.5 (MMBtu/day) to 9.4 and 4.4 (MMBtu/day) respectively. The MBE of CHW and HW changed from -1.0 and 0.0 (MMBtu/day) to –1.0 and –0.3 (MMBtu/day).

There is still room for small improvements in CHW and HW consumption that may be provided by hourly calibration.

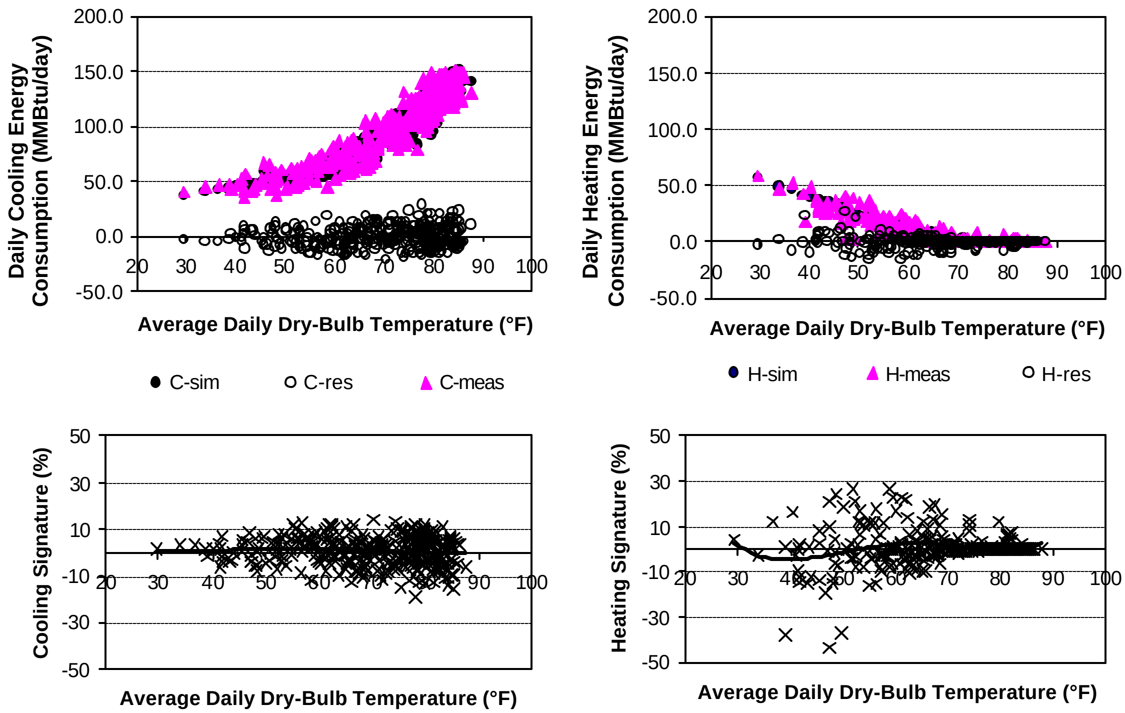


Figure 33. Cooling and heating simulation charts after iteration 4

Step 9. The results of iteration 4 were quite good. However hourly calibration might fine-tune the simulation model. The Zachry Engineering Center includes offices, classrooms, laboratories and computer rooms and is open 24 hours per day, 365 days per year with heaviest occupancy during normal working hours between 8 a.m. and 6 p.m. on weekdays.

The available metered data for electricity consists of Whole Building Electricity consumption (WBE) and Motor Control Center (MCC) electricity consumption. The MCC electricity is the consumption of the HVAC fans and pumps, which is largely consumed in unconditioned zones. Therefore the internal load for the building due to the electricity consumption can be approximated as (WBE – MCC). The MCC electricity consumption was relatively constant throughout 1994 at approximately 200kWh/h.

Figures 34 to 36 show the internal load pattern vs. the time of the day for weekdays, weekends, and university vacation periods when classes are not in session. The curves on the measured electricity graphs (left side) connect the average values for the electricity consumption for each hour of the day. The occupancy schedules (right side) are calculated from the averaged electricity consumption by dividing the averaged electricity consumption values by the maximum hourly average electricity consumption for the year (1075.95kWh/h).

The maximum value of measured (WBE – MCC) is 4.13 W/ft^2 (1075.95 kWh/h for the building). The original occupancy schedule was 1.0 for every hour of the year with a calibrated average internal heat gain value of 3.0 W/ft^2.

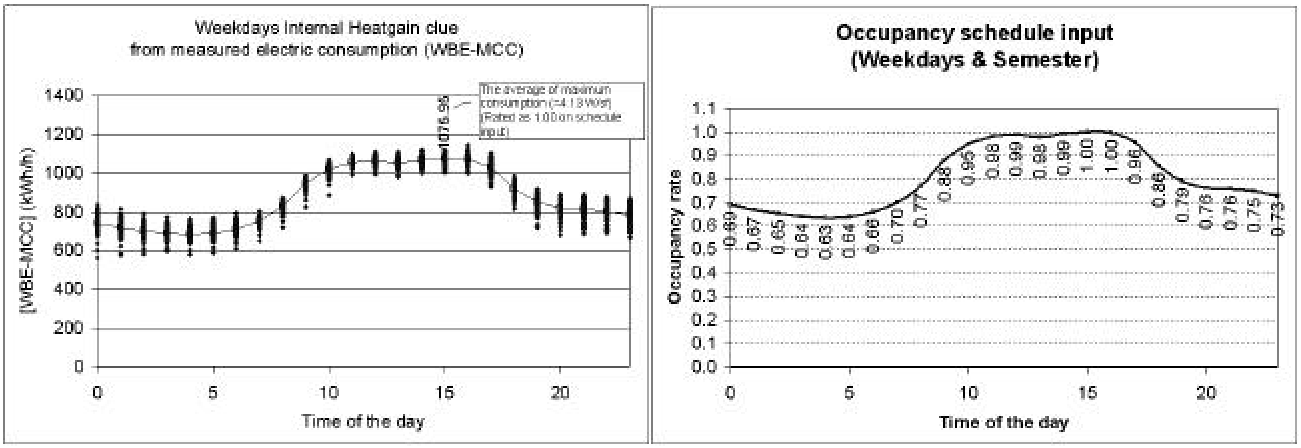


Figure 34. Measured electricity consumption [WBE-MCC] for weekday periods and occupancy schedule input based on the [WBE-MCC] pattern for weekdays.

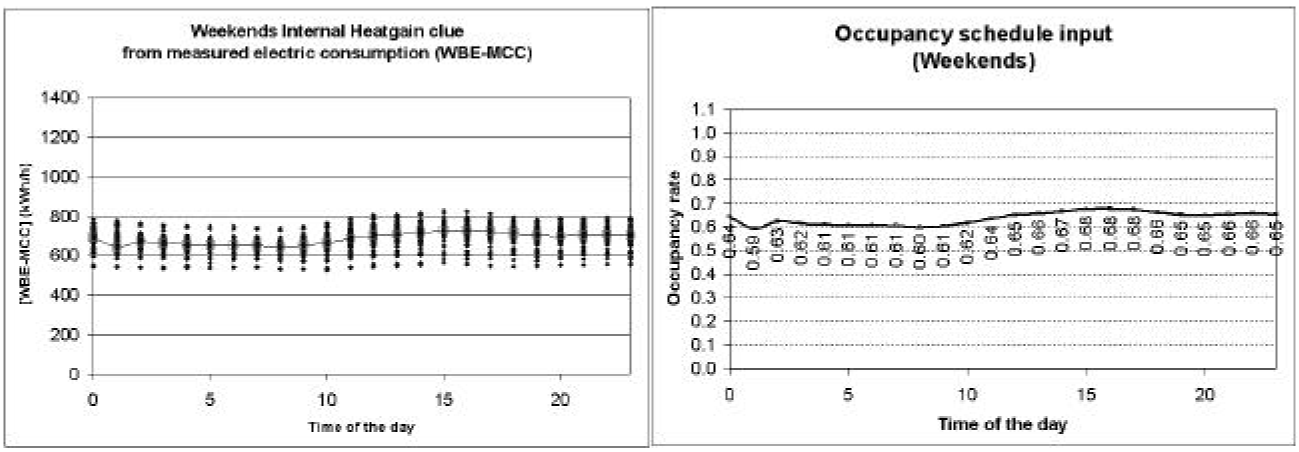


Figure 35. Measured electricity consumption [WBE-MCC] for weekend periods and occupancy schedule input based on the [WBE-MCC] pattern for weekends.

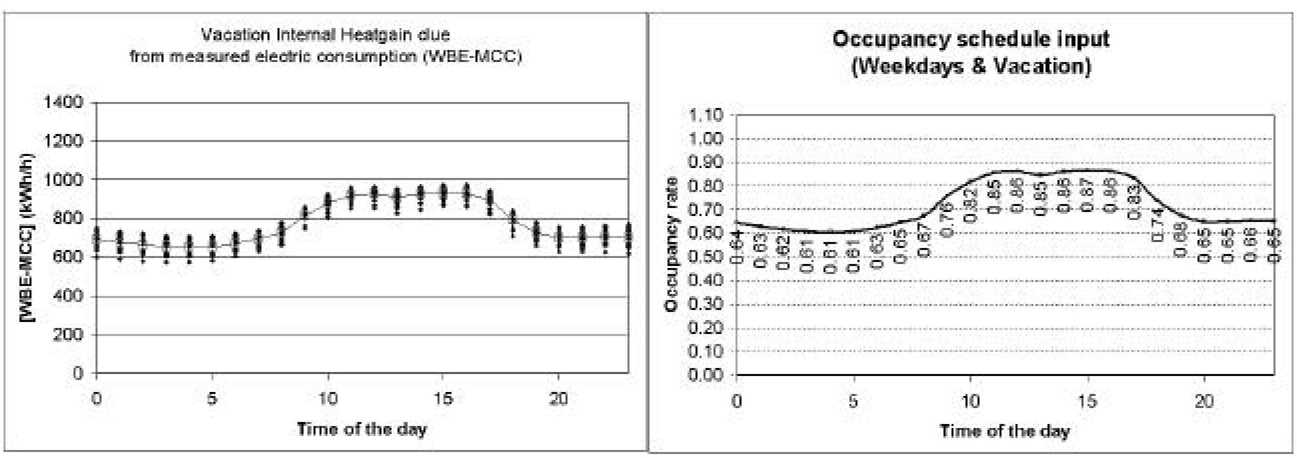


Figure 36. Measured electricity consumption [WBE-MCC] for vacation periods and occupancy schedule input based on the [WBE-MCC] pattern for vacation periods.

The results of the hourly calibration are shown in figure 37. While the RMSE for HW did not change from 4.4 MMBtu/day, the RMSE for CHW improved from 9.4 MMBtu/day to 7.2 MMBtu/day. The MBE is unchanged from the last iteration at -1.0 and -0.3 MMBtu/day for CHW and HW respectively. The calibration is finished.

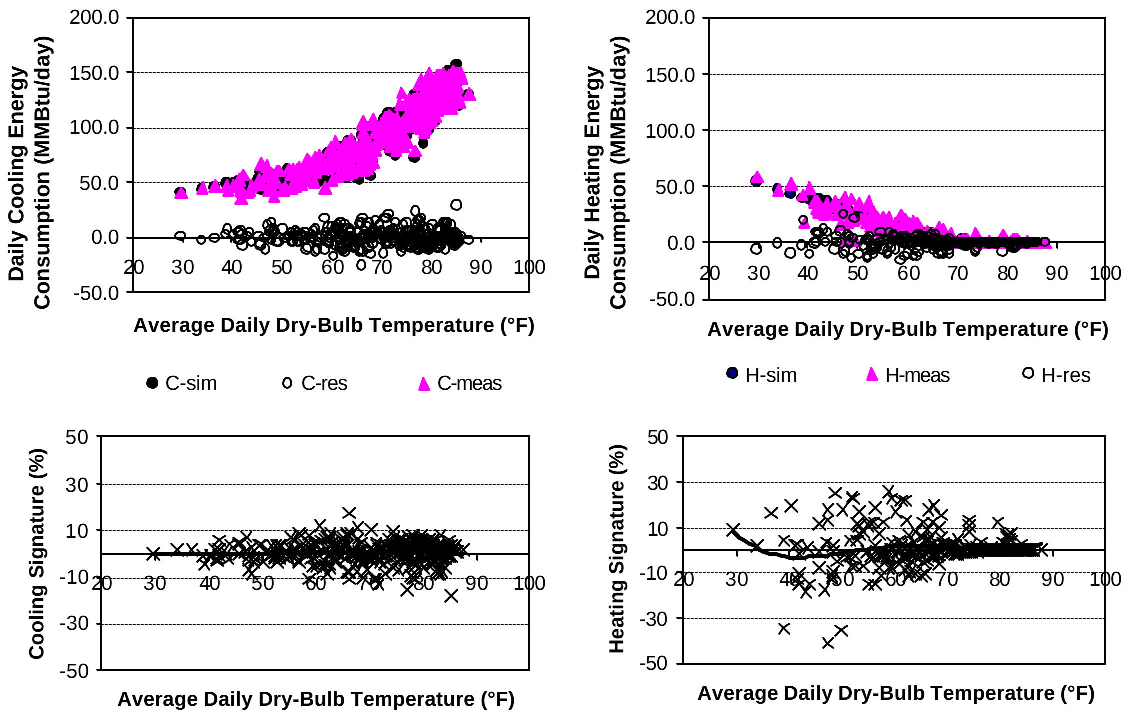


Figure 37. Calibrated simulation charts for case study 2

The calibration procedure using calibration signatures has been illustrated for the Zachry Engineering Center at Texas A&M University. Hourly fine-tuning with measured electricity consumption inside the conditioned zone appreciably reduced the CHW RMSE. Five calibration steps, reduced the RMSE for CHW and HW from 15.4 and 7.0 MMBtu/day to 7.2 and 4.4 MMBtu/day respectively.

This calibration method requires some engineering sense of appropriate values, but can significantly speed the process, even for engineers without a great deal of simulation experience. The use of calibration signatures and characteristic signatures help decide which parameter(s) should be changed and gives some indication of the size of change required.

A summary of the calibration iterations is shown in Table 6.

Table 6. Summary of calibration steps

Simulation parameter and alteration		Cooling (MMBtu/day)		Heating (MMBtu/day)	
		RMSE	**MBE**	**RMSE**	**MBE**
Initial simulation:		15.4	4.0	7.0	-3.5
Internal heat gain (av.): Outside air flow (ext.): Wall U-value: Window U-value: Hot deck temperature: Cold deck temperature:	3.1 → 2.7 W/ft^2 0.2 → 0.1 cfm/ft^2 0.08 → 0.1 Btu/ft^2.hr.°F 0.7 → 0.75 Btu/ft^2.hr.°F Increased by 5°F Decreased by 3°F	12.0	-7.5	5.6	-2.4
Internal heat gain: Hot deck temperature:	2.7 → 3.0 W/ft^2 130 °F at T_{OA}=20 °F 105 °F at T_{OA}=42 °F 90 °F at T_{OA}=50 °F 70 °F at T_{OA}=62 °F	9.5	-0.5	5.0	-1.8
Outside air flow (ext.): Window U-value: Hot deck temperature:	0.1 → 0.14 cfm/ft^2 0.75 → 1.0 Btu/ft^2.hr.°F 130 °F at T_{OA}=20 °F 105 °F at T_{OA}=42 °F 95 °F at T_{OA}=50 °F 75 °F at T_{OA}=62 °F 70 °F at T_{OA}=85 °F	9.5	-1.0	4.5	0.0
Window U-value:	1.0 → 0.85 Btu/ft^2.hr.°F	9.4	-1.0	4.4	-0.3
Hourly calibration: ◆ Internal gain: ◆ Occupancy schedule:	 3.0 (av.) → 4.13 W/ft^2 (max.) Figures 34-36 (right)	7.2	-1.0	4.4	-0.3

CONCLUSIONS

This manual describes a method that can be used to facilitate the calibration of a building system simulation to measured data. The method uses a graphical format that intuitively summarizes and describes the differences between the simulation results and the measured data, referred to as a Calibration Signature. By creating a library of shapes for certain known errors, we can provide clues to the analyst to use in identifying what simulation input errors may be causing the discrepancies. These are referred to as Characteristic Calibration Signatures.

This manual describes how the signatures are defined, and how they are used in calibration. It provides two fairly simple examples of their use, based on synthetic data, and provides two real-world examples that illustrate how to handle additional challenges in the calibration process. The Characteristic Calibration Signatures are provided in the Appendices for four different system types, and for three different California climates.

This method was found to be quite useful in several examples, and its use should enable a broader array of analysts to produce better quality building simulations. These more reliable simulations can be used for a host of purposes, including retrofit expected savings analysis, building optimization, commissioning, and fault detection.

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APPENDIX A: DESCRIPTION OF BUILDING AND SYSTEM MODELS USED TO CREATE CHARACTERISTIC SIGNATURES

Characteristic calibration signatures are provided in this manual for four different system types and three different climates:

System Types:	*Climates:*
Single-duct, constant-air-volume (SDCV)	Pasadena
Single-duct, variable-air-volume (SDVAV)	Sacramento
Dual-duct, constant-air-volume (DDCV)	Oakland
Dual-duct, variable-air-volume (DDVAV)	

Figures A-1 and A-2 show schematics of the single-duct and dual-duct systems used to generate the characteristic signatures in this manual. Constant-air-volume systems have constant air flow rate fans, while variable-air-volume systems have variable air flow rate fans.

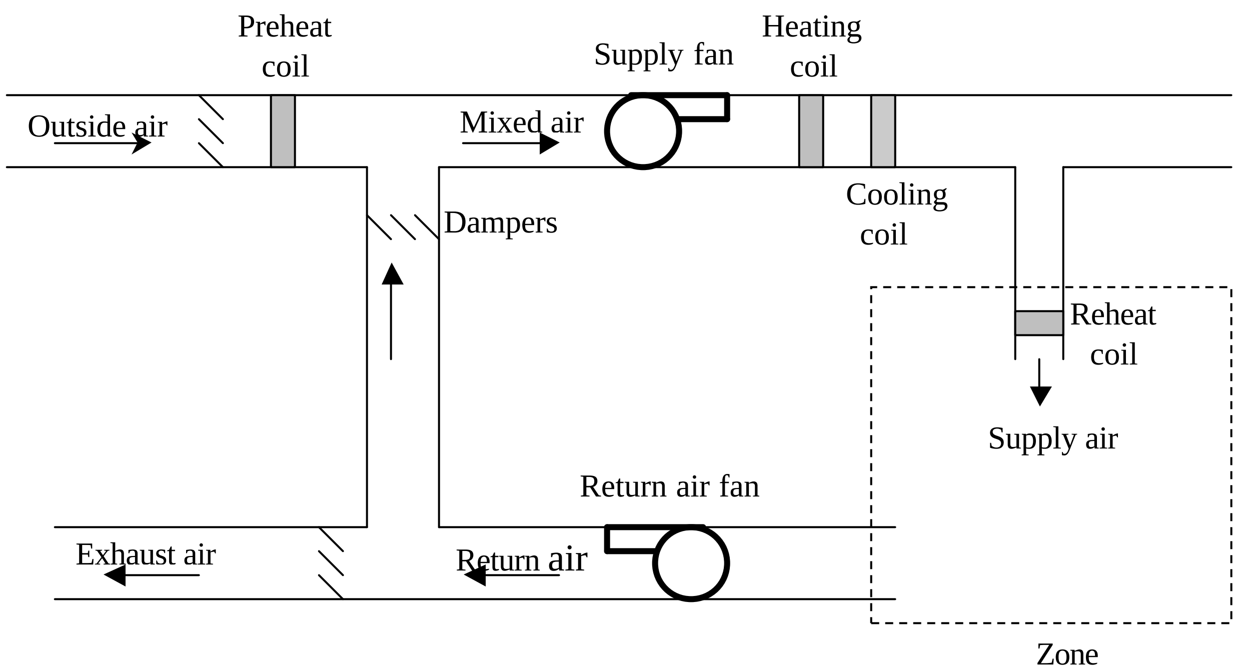


Figure A-1. Schematic of a single-duct air handler

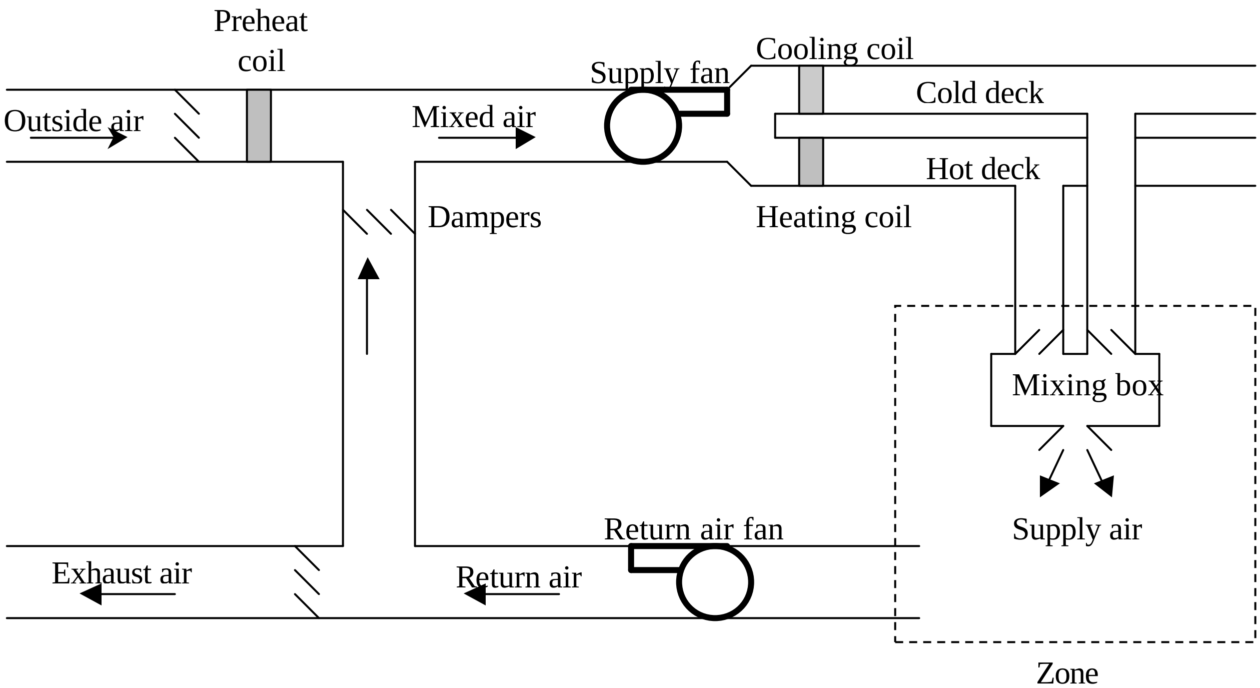


Figure A-2. Schematic of a dual-duct air handler

The operational equations that define the models used for SDCV, SDVAV, DDCV and DDVAV systems are shown respectively in Figures A-3 to A-6, with the nomenclature defined in Table A-1.

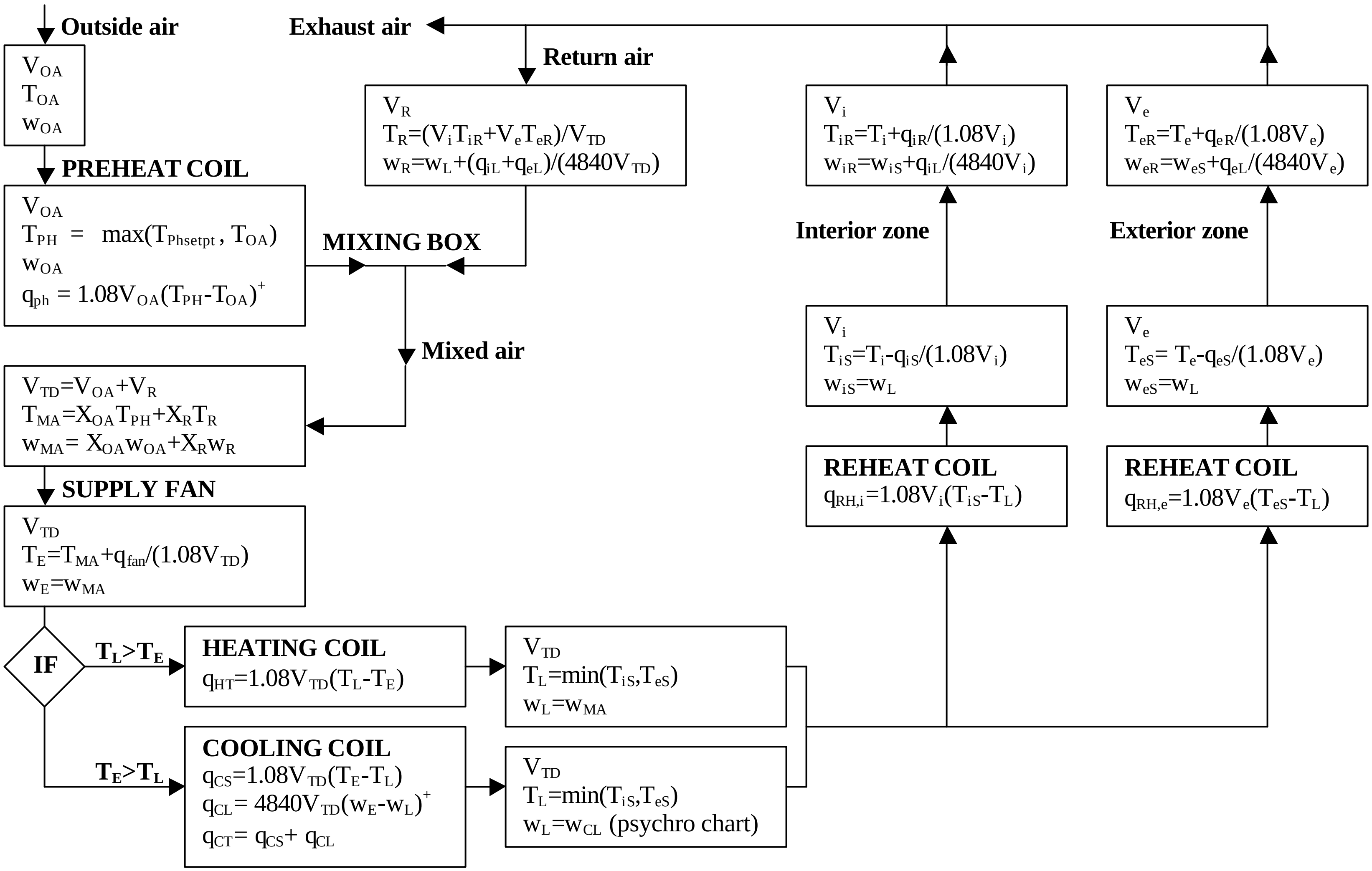


Figure A-3. Operational equations for a SDCV System

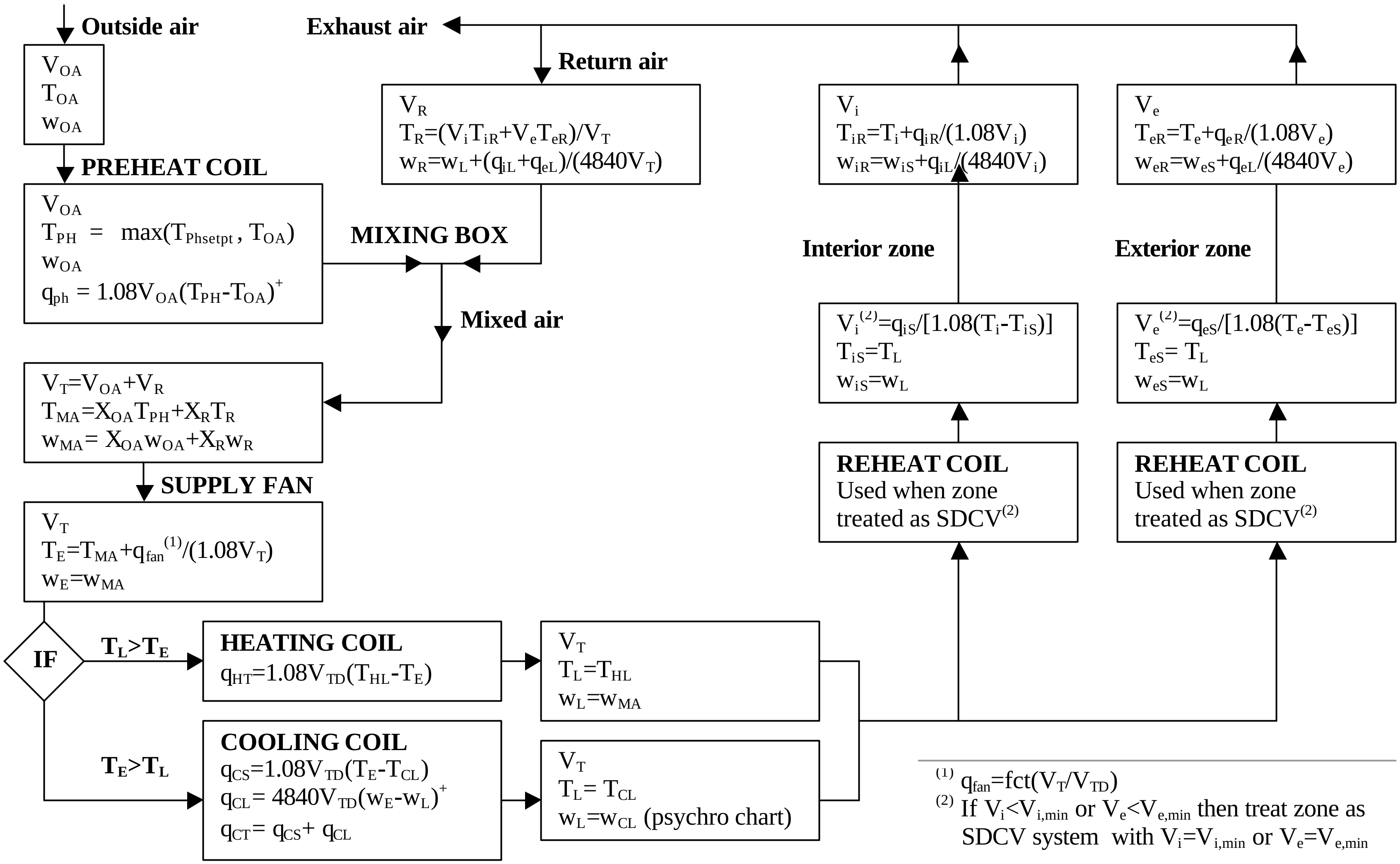


Figure A-4. Operational equations for a SDVAV System

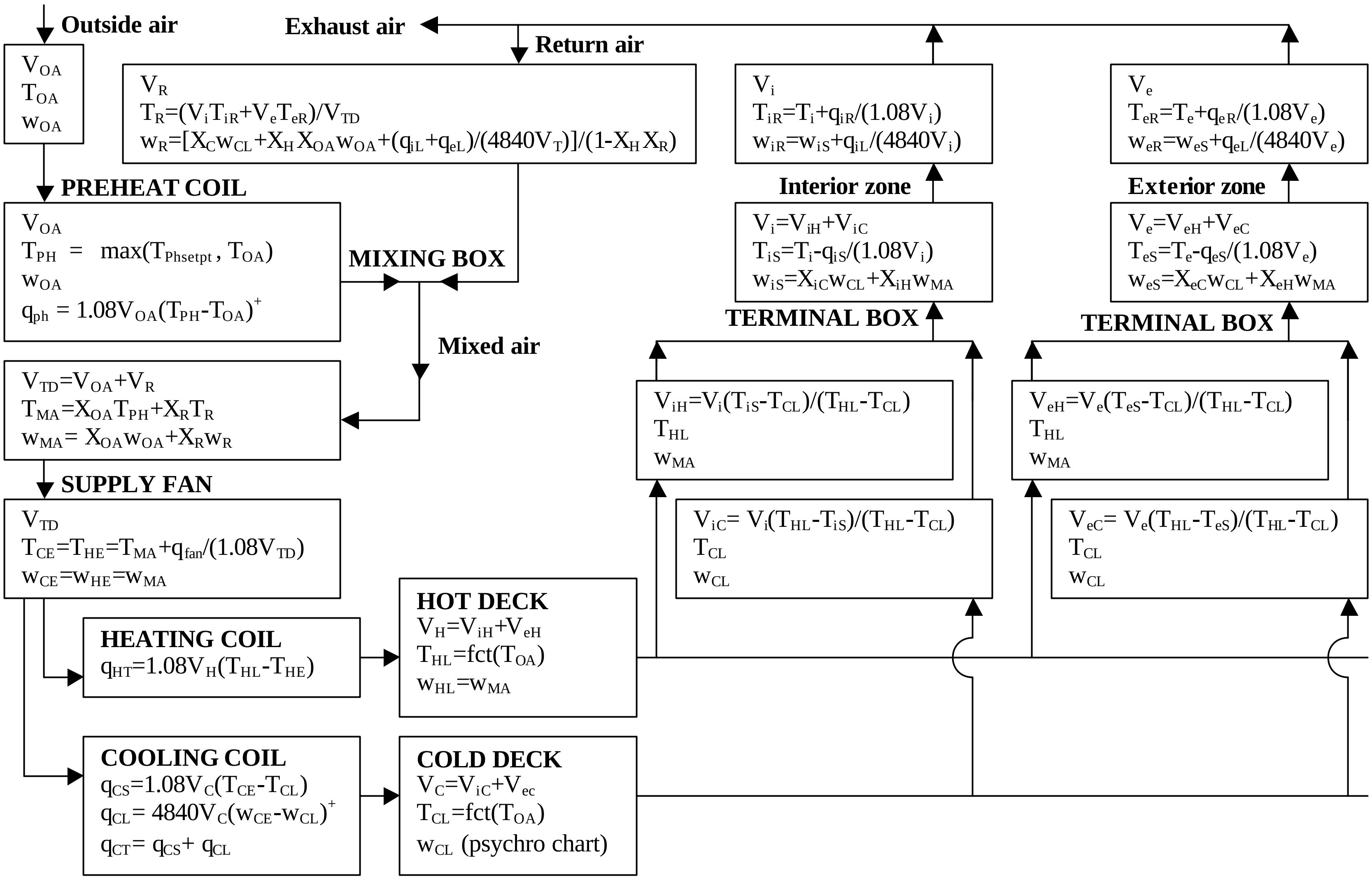
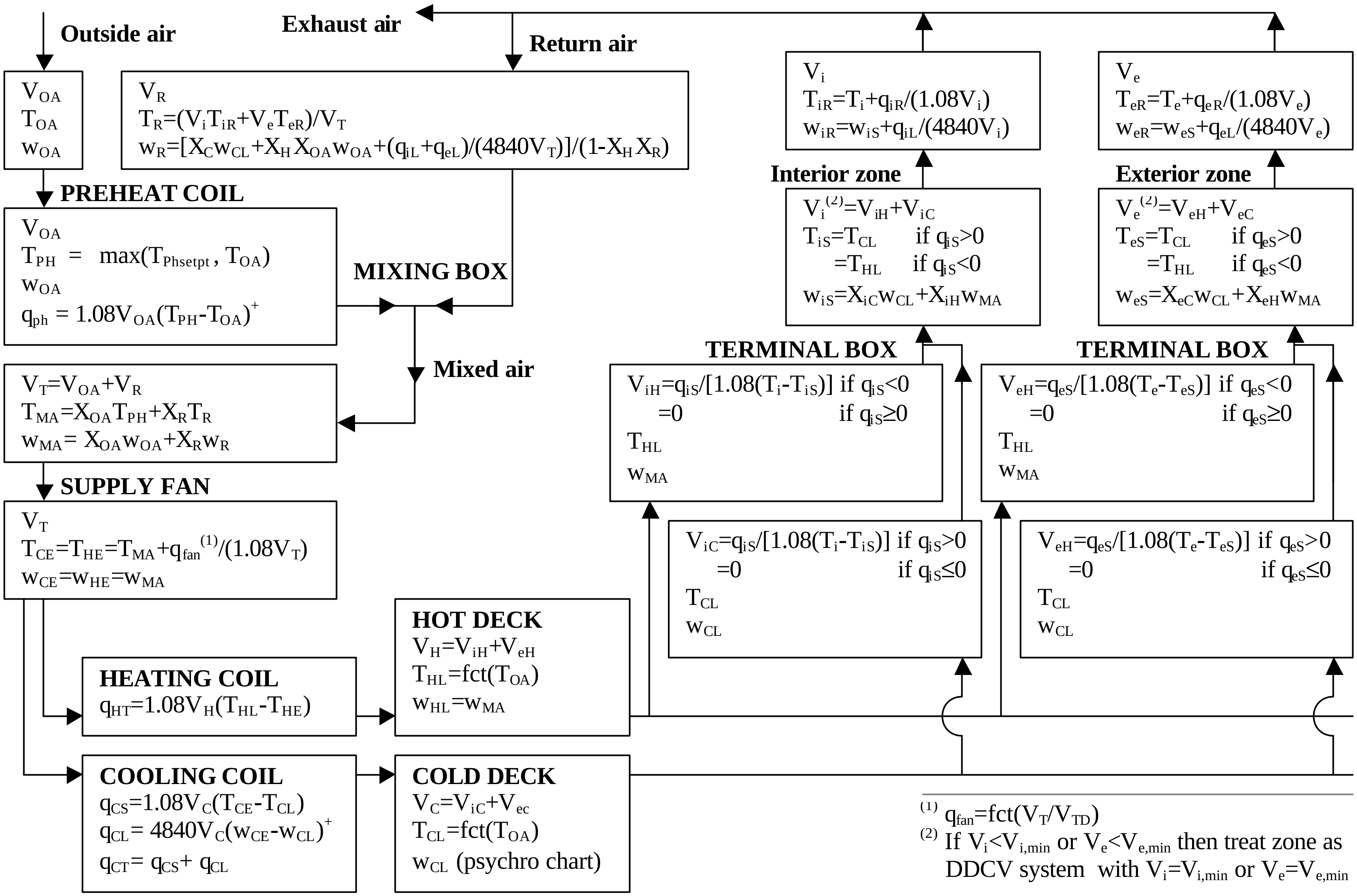


Figure A-5. Operational equations for a DDCV System



(1) $q_{fan}=fct(V_T/V_{TD})$
(2) If $V_i<V_{i,min}$ or $V_e<V_{e,min}$ then treat zone as DDCV system with $V_i=V_{i,min}$ or $V_e=V_{e,min}$

Figure A-6. Operational equations for a DDVAV System

Table A-1. Nomenclature for operational equations

Variable	Definition	Unit
ΔT_{SF}	Supply air fan Temperature rise	°F
q_{CL}	Cooling coil latent load	Btu/hr
q_{CS}	Cooling coil sensible load	Btu/hr
q_{CT}	Cooling coil total load	Btu/hr
q_{eL}	Exterior zone latent load	Btu/hr
q_{eR}	Exterior zone return air heat gain	Btu/hr
q_{eS}	Exterior zone sensible load	Btu/hr
q_{HT}	Heating coil sensible load	Btu/hr
q_{iL}	Interior zone latent load	Btu/hr
q_{iR}	Interior zone return air heat gain	Btu/hr
q_{iS}	Interior zone sensible load	Btu/hr
q_{ph}	Preheat coil load	Btu/hr
$q_{RH,i}$	Interior zone reheat coil load	Btu/hr
$q_{RH,e}$	Exterior zone reheat coil load	Btu/hr
T_{CE}	Cooling coil entering air dry bulb Temperature	°F
T_{CL}	Cooling coil leaving air dry bulb Temperature	°F
T_e	Exterior zone design air dry bulb Temperature	°F
T_E	Coil entering air dry bulb Temperature	°F
T_{eR}	Exterior zone return air dry bulb Temperature	°F
T_{eS}	Exterior zone supply air dry bulb Temperature	°F
T_{HE}	Heating coil entering air dry bulb Temperature	°F
T_{HL}	Heating coil leaving air dry bulb Temperature	°F
T_i	Interior zone design air dry bulb Temperature	°F
T_{iR}	Interior zone return air dry bulb Temperature	°F
T_{iS}	Interior zone supply air dry bulb Temperature	°F
T_L	Coil leaving air dry bulb Temperature	°F
T_{MA}	Mixed air dry bulb Temperature	°F
T_{OA}	Outside air dry bulb Temperature	°F
T_{PH}	Preheat coil leaving air dry bulb Temperature	°F
T_R	Return air dry bulb Temperature	°F
V_C	Cold Deck air volume	ft^3/min
V_e	Exterior zone supply air volume	ft^3/min
$V_{e,min}$	Exterior zone minimum supply air volume	ft^3/min

Table A-1. Nomenclature for operational equations (continued)

Variable	Definition	Unit
V_{eC}	Exterior zone cold air volume	ft^3/min
V_{eH}	Exterior zone hot air volume	ft^3/min
V_H	Hot Deck air volume	ft^3/min
V_i	Interior zone supply air volume	ft^3/min
$V_{i,min}$	Interior zone minimum supply air volume	ft^3/min
V_{iC}	Interior zone cold air volume	ft^3/min
V_{iH}	Interior zone hot air volume	ft^3/min
V_{OA}	Outside air volume	ft^3/min
V_R	Return air volume	ft^3/min
V_T	Total air volume	ft^3/min
V_{TD}	Design total air volume	ft^3/min
w_{CE}	Cooling coil entering air humidity ratio	lb_w/lb_a
w_{CL}	Cooling coil leaving air humidity ratio	lb_w/lb_a
w_E	Coil entering air humidity ratio	lb_w/lb_a
w_{eR}	Exterior zone return air humidity ratio	lb_w/lb_a
w_{eS}	Exterior zone supply air humidity ratio	lb_w/lb_a
w_{HE}	Heating coil entering air humidity ratio	lb_w/lb_a
w_{HL}	Heating coil leaving air humidity ratio	lb_w/lb_a
w_{iR}	Interior zone return air humidity ratio	lb_w/lb_a
w_{iS}	Interior zone supply air humidity ratio	lb_w/lb_a
w_L	Coil leaving air humidity ratio	lb_w/lb_a
w_{MA}	Mixed air humidity ratio	lb_w/lb_a
w_{OA}	Outside air humidity ratio	lb_w/lb_a
w_R	Return air humidity ratio	lb_w/lb_a
X_C	Cold Deck air volume ratio = V_C/V_T	Dimensionless
X_{eC}	Exterior zone cold air volume ratio = V_{eC}/V_e	Dimensionless
X_{eH}	Exterior zone hot air volume ratio = V_{eH}/V_e	Dimensionless
X_H	Hot Deck air volume ratio = V_H/V_T	Dimensionless
X_{iC}	Interior zone cold air volume ratio = V_{iC}/V_i	Dimensionless
X_{iH}	Interior zone hot air volume ratio = V_{iH}/V_i	Dimensionless
X_{OA}	Ouside air volume ratio = V_{OA}/V_T	Dimensionless
X_R	Return air volume ratio = V_R/V_T	Dimensionless

A prototypical 6-floor office building was simulated to generate the characteristic calibration signatures. Figure A-7 shows the floor plan of the building. Major characteristics of the building and its systems are shown in Table A-2.

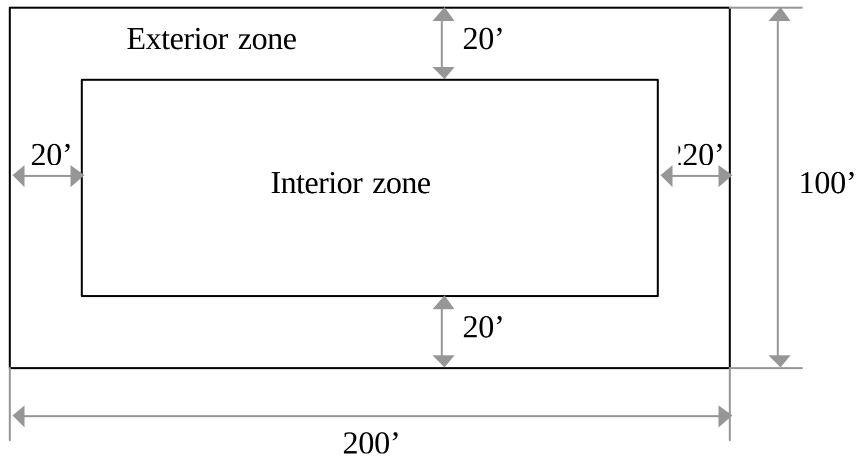


Figure A-7. Building floor plan

Table A-2. Baseline building and system characteristics

Parameter	Baseline value
Conditioned floor area	120,000 ft^2
Interior zone ratio	0.5
Exterior wall area	37,800 ft^2
Exterior wall U-value	0.1 Btu/ft^2.hr.°F
Window area	16,200 ft^2
Window U-value	0.7 Btu/ft^2.hr.°F
Roof area	20,000 ft^2
Roof U-value	0.09 Btu/ft^2.hr.°F
Design room temperature T_{room}	73 °F
Total air flow rate	1 cfm/ft^2
Minimum air flow rate -VAV systems-	0.5 cfm/ft^2
Outside air flow rate	0.15 cfm/ft^2
Economizer	None
Average internal heat gain Q_{int}	1.4 W/ft^2
Solar gains in Btu/hr/ft^2 of building floor area (linear between defined points)	◆ Pasadena: 0.77 at T_{OA-min}=32 °F 0.98 at T_{OA-max}=97 °F ◆ Sacramento: 0.49 at T_{OA-min}=27 °F 1.27 at T_{OA-max}=107 °F ◆ Oakland: 0.54 at T_{OA-min}=32 °F 1.08 at T_{OA-max}=82 °F
Air infiltration	None – building positively pressurized
Average occupancy	200 ft^2/person
Return air and room air temperature difference	2 °F
Cold deck temperature T_c	55 °F
Hot deck schedule T_h -DD systems- (linear between defined points and constant outside lower and higher limits)	110 °F at T_{OA}=40 °F 80 °F at T_{OA}=70 °F 70 °F at T_{OA}=100 °F
Preheat location	Outside air
Preheat temperature T_{ph} schedule	45 °F for T_{OA}<45 °F

The AirModel simulation program approximates solar gains as a linear function of outside air temperature as recommended by Knebel (1983). Required inputs of winter and summer average solar gains for the three cities were calculated using the Klein-Theilacker method (Duffie and Beckman, 1991).

The characteristic signatures were generated by running the baseline simulation with a selected weather file, then altering key calibration parameters one by one and calculating the impact on total cooling and heating energy consumption. Table A-3 shows the alterations of the key calibration parameters used to generate the characteristic signatures for the four AHU types. These calibration parameters have a significant influence on energy consumption, are perceived as having a significant influence (and thus are commonly considered for making calibration changes) or are those in which the authors have frequently seen errors.

Table A-3. Alterations of calibration parameters used to generate characteristic signatures for the four AHU types

Calibration parameter	Baseline	Alteration			
		SDVAV	SDCV	DDVAV	DDCV
Cold deck temperature T_c (°F)	55	54	54	53	52
Hot deck temperature T_h (°F) vs. outdoor temperature T_{OA}: ◆ **At T_{OA}= 40 °F** ◆ **At T_{OA}= 70 °F** ◆ **At T_{OA}= 100 °F**	 110 80 70			Increased by 3 °F	Increased by 2 °F
Minimum air flow rate (cfm/ft^2)	0.5	0.47		0.40	
Supply air flow rate (cfm/ft^2)	1		1.08		1.08
Conditioned floor area (ft^2)	120,000	130,000			
Pre-heat temperature T_{ph} (°F)	45	55			
Internal gains Q_{int} (W/ft^2)	1.4	1.2	1	1.2	1
Outside air flow rate (cfm/ft^2)	0.15	0.20			
Room Temperature T_{room} (°F)	73	74	74	73	74
Envelope U-value (Btu/ft^2.hr.°F) ◆ **Window** ◆ **Exterior wall** ◆ **Roof**	 0.7 0.1 0.09	Decreased by 15%	Decreased by 20%	Decreased by 15%	Decreased by 20%
Economizer	None	Temperature economizer at [40,58°F]			

APPENDIX B: DESCRIPTION OF BUILDING AND SYSTEM MODEL USED IN ILLUSTRATIVE EXAMPLES

The two illustrative examples use the same prototypical 6-floor office building shown in Figure A-7. The HVAC system used is the DDCV system shown in Figure A-2 with the operational equations shown in Figure A-5. The two examples were simulated with AirModel using Pasadena weather data. Table B-1 shows key characteristics of the building and system model.

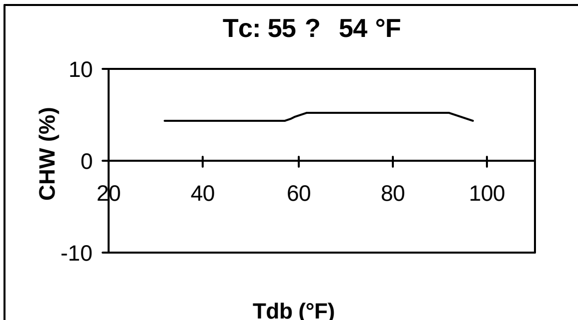
Table B-1. Key building and system characteristics of the building used in the illustrative examples

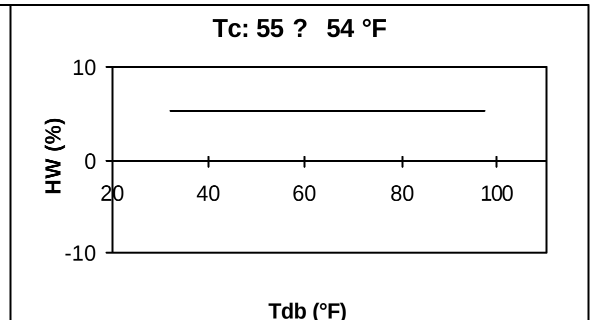
Parameter	Value
Conditioned floor area	120,000 ft^2
Interior zone ratio	0.5
Exterior wall area	37,800 ft^2
Exterior wall U-value	0.1 Btu/ft^2.hr.°F
Window area	16,200 ft^2
Window U-value	0.7 Btu/ft^2.hr.°F
Roof area	20,000 ft^2
Roof U-value	0.09 Btu/ft^2.hr.°F
Design room temperature T_{room}	73 °F
Maximum room relative humidity	50 %
Total air flow rate	1.2 cfm/ft^2
Outside air flow rate	0.1 cfm/ft^2
Economizer	None
Average internal heat gain Q_{int}	0.8 W/ft^2
Solar gains in Btu/hr/ft^2 of building floor area	0.77 at $T_{OA\text{-}min}$=32 °F 0.98 at $T_{OA\text{-}max}$=97 °F
Air infiltration	None
Average occupancy	200 ft^2/person
Difference between return and room air temperatures	2 °F
Cold deck temperature T_c	55 °F
Hot deck schedule T_h (linear between defined points and constant outside lower and higher limits)	110 °F at T_{OA}=40 °F 80 °F at T_{OA}=70 °F 70 °F at T_{OA}=100 °F
Preheat location	Outside air
Preheat schedule T_{ph}	45 °F for T_{OA}<45 °F

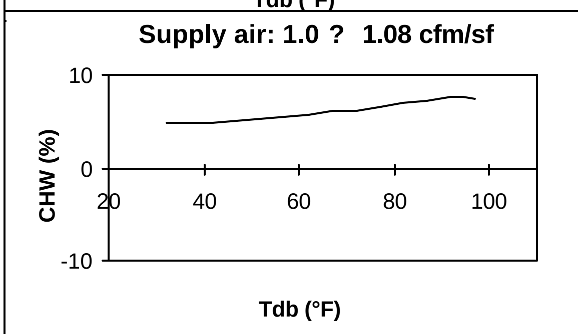
The solar gains were calculated using the Klein-Theilacker method (Duffie and Beckman, 1991).

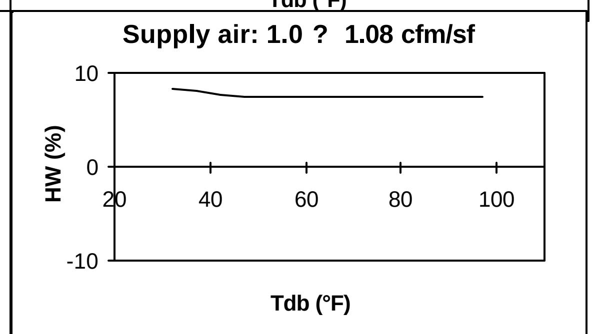
APPENDIX C: CHARACTERISTIC SIGNATURES FOR SDCV SYSTEMS

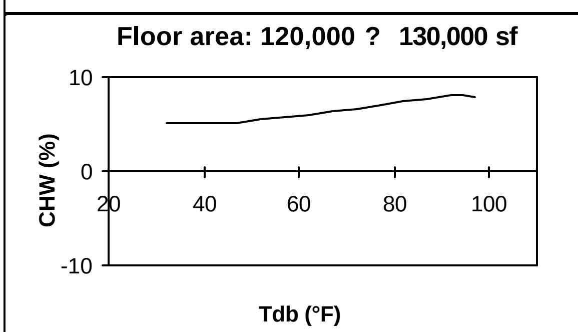
APPENDIX C-1: SDCV SYSTEM IN PASADENA

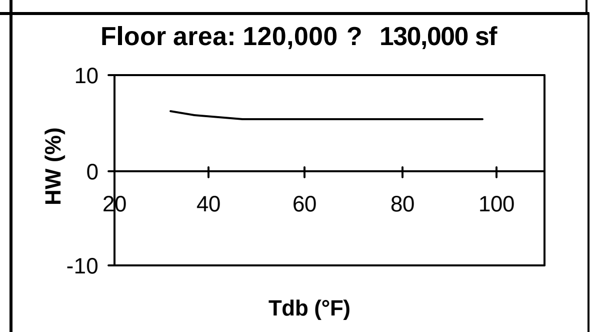


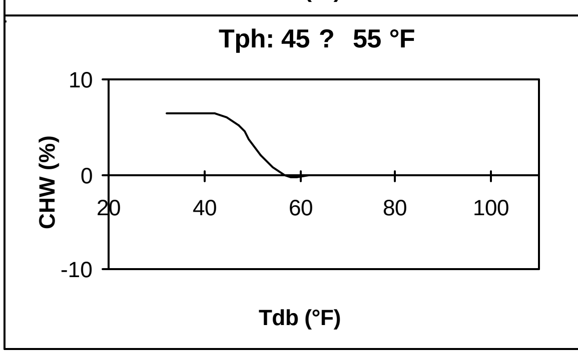


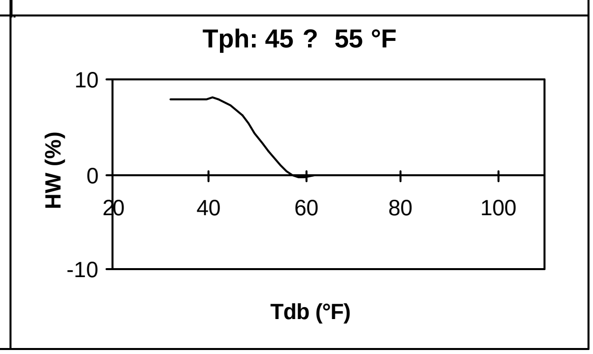


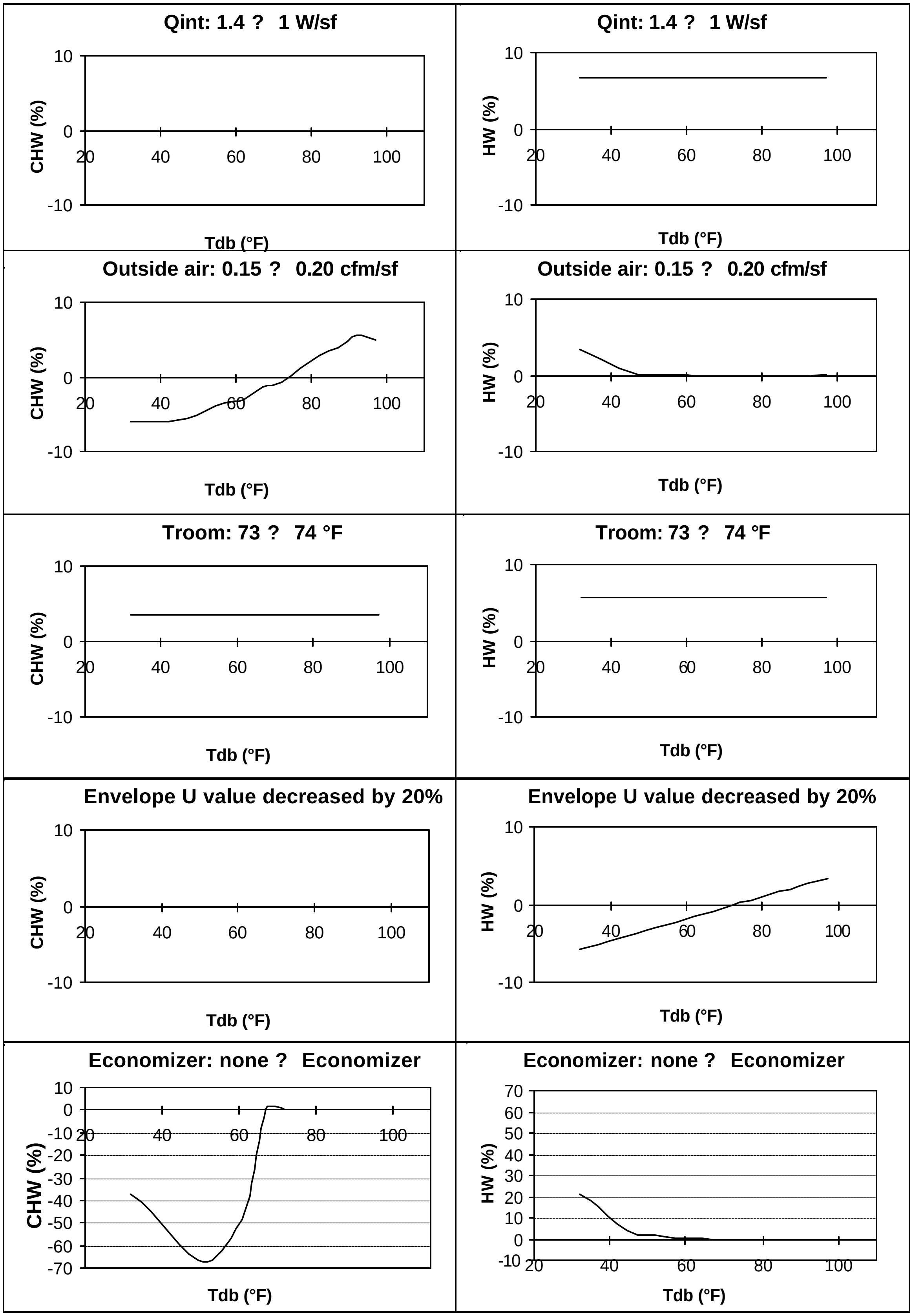






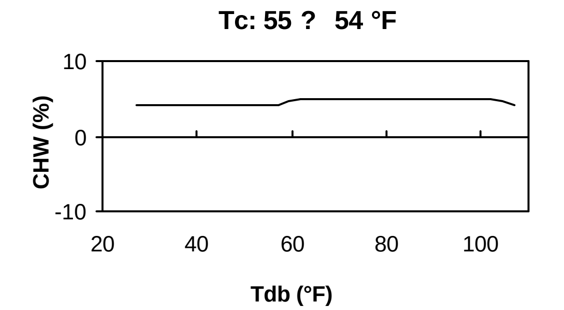


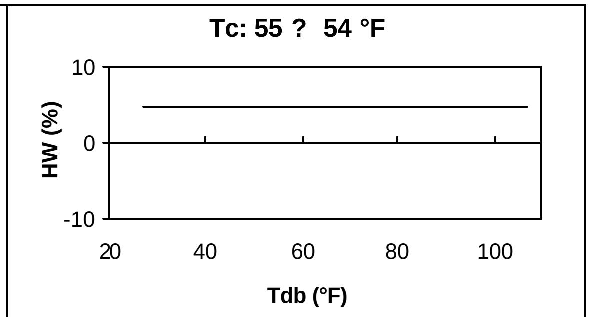


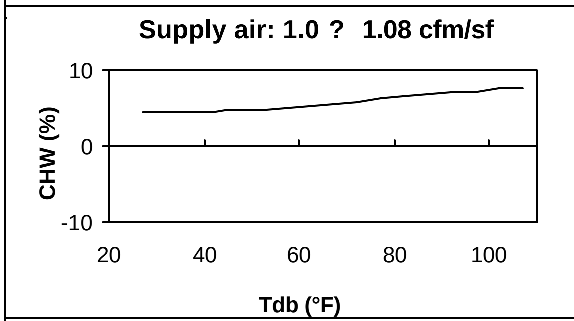


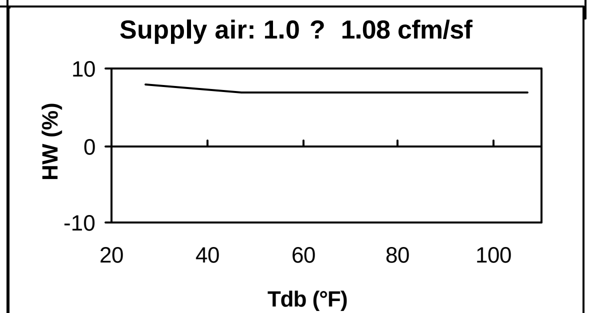
Qint: 1.4 ? 1 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U value decreased by 20%
CHW (%)
Tdb (°F)
Envelope U value decreased by 20%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

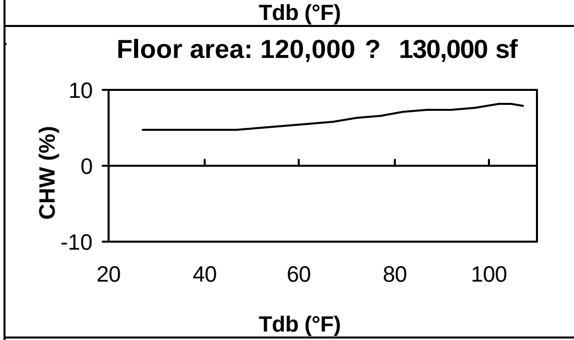
APPENDIX C-2: SDCV SYSTEM IN SACRAMENTO

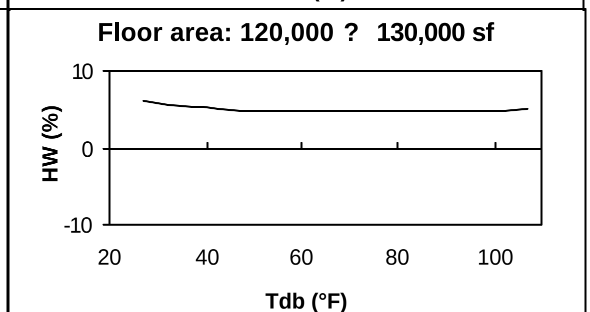


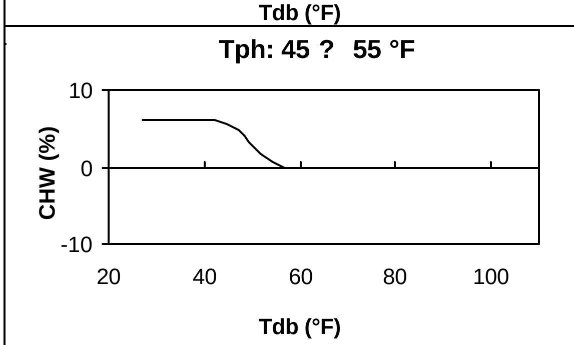


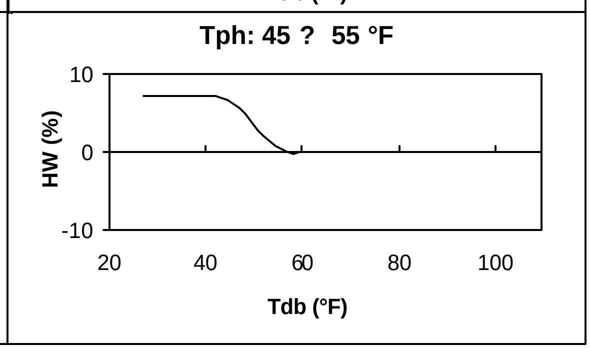


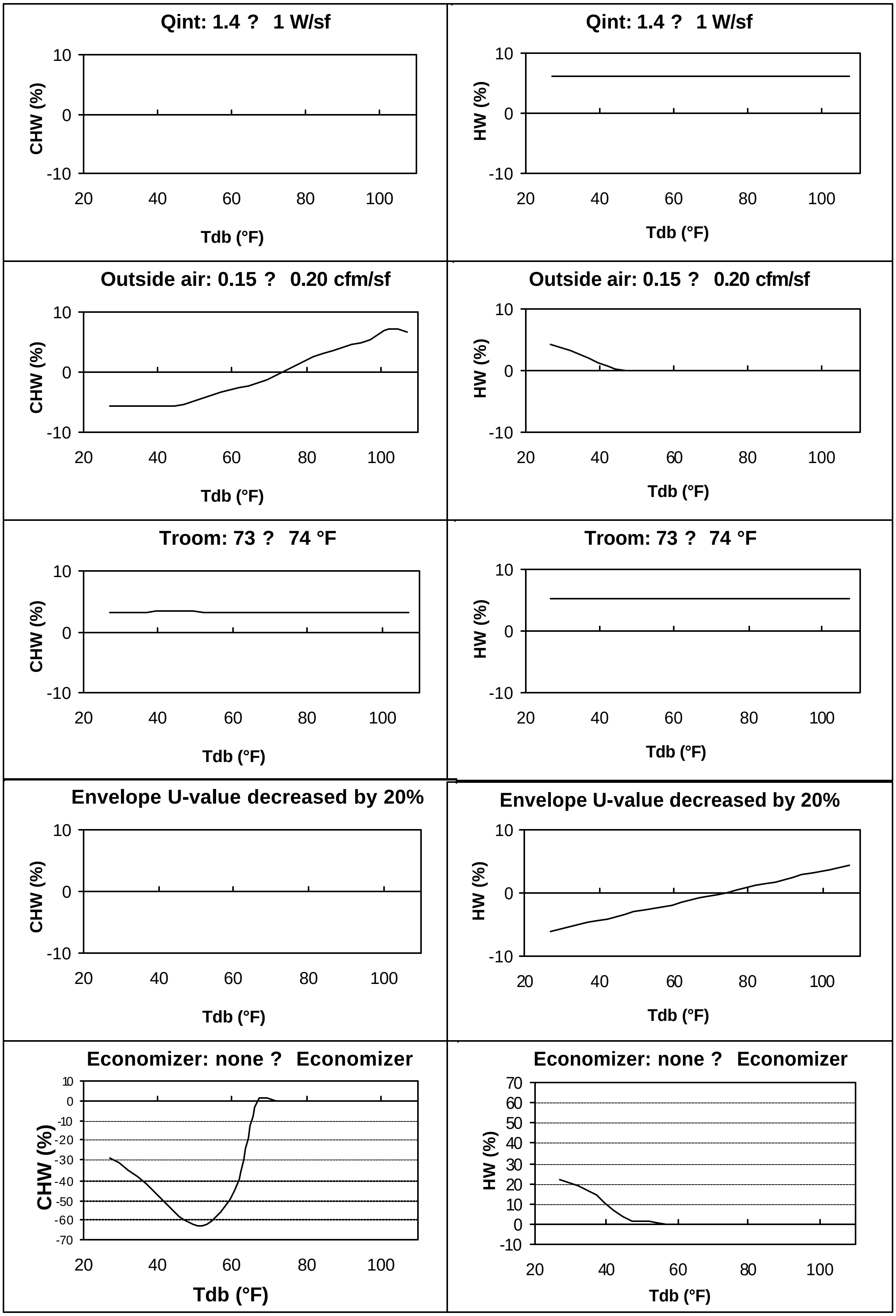




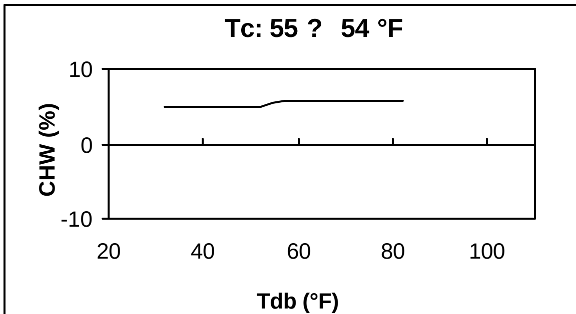


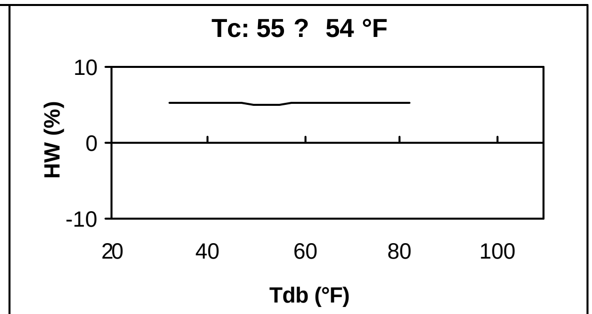


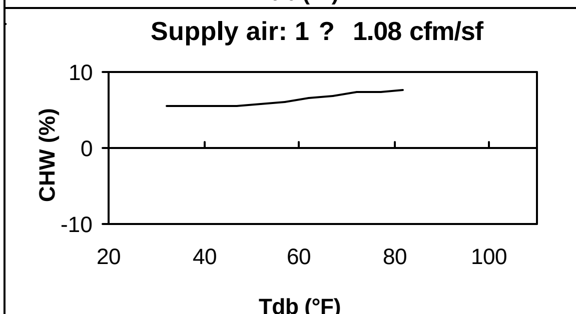


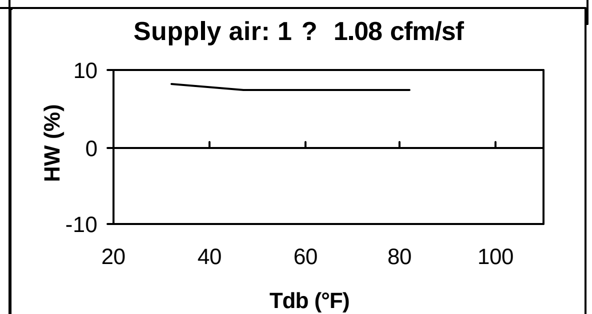

Qint: 1.4 ? 1 W/sf
CHW (%)
HW (%)
Outside air: 0.15 ? 0.20 cfm/sf
Troom: 73 ? 74 °F
Envelope U-value decreased by 20%
Economizer: none ? Economizer
Tdb (°F)
10
0
-10
-20
-30
-40
-50
-60
-70
20
30
40
50
60
70
80
100

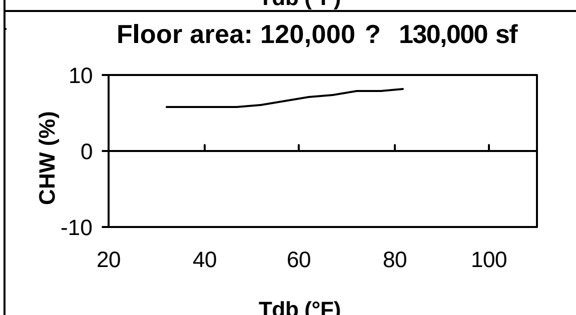
APPENDIX C-3: SDCV SYSTEM IN OAKLAND

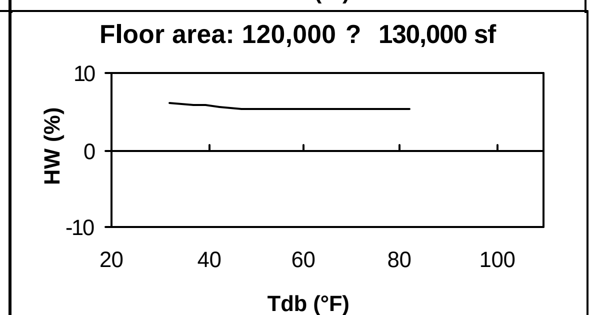


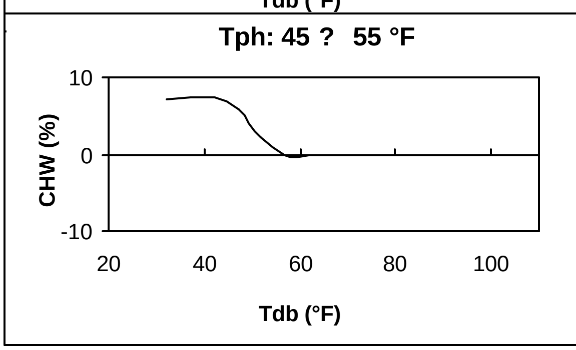


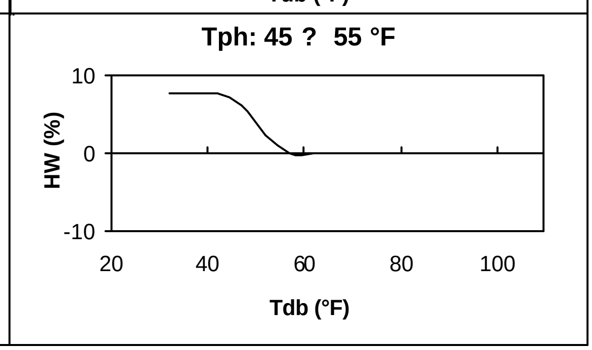


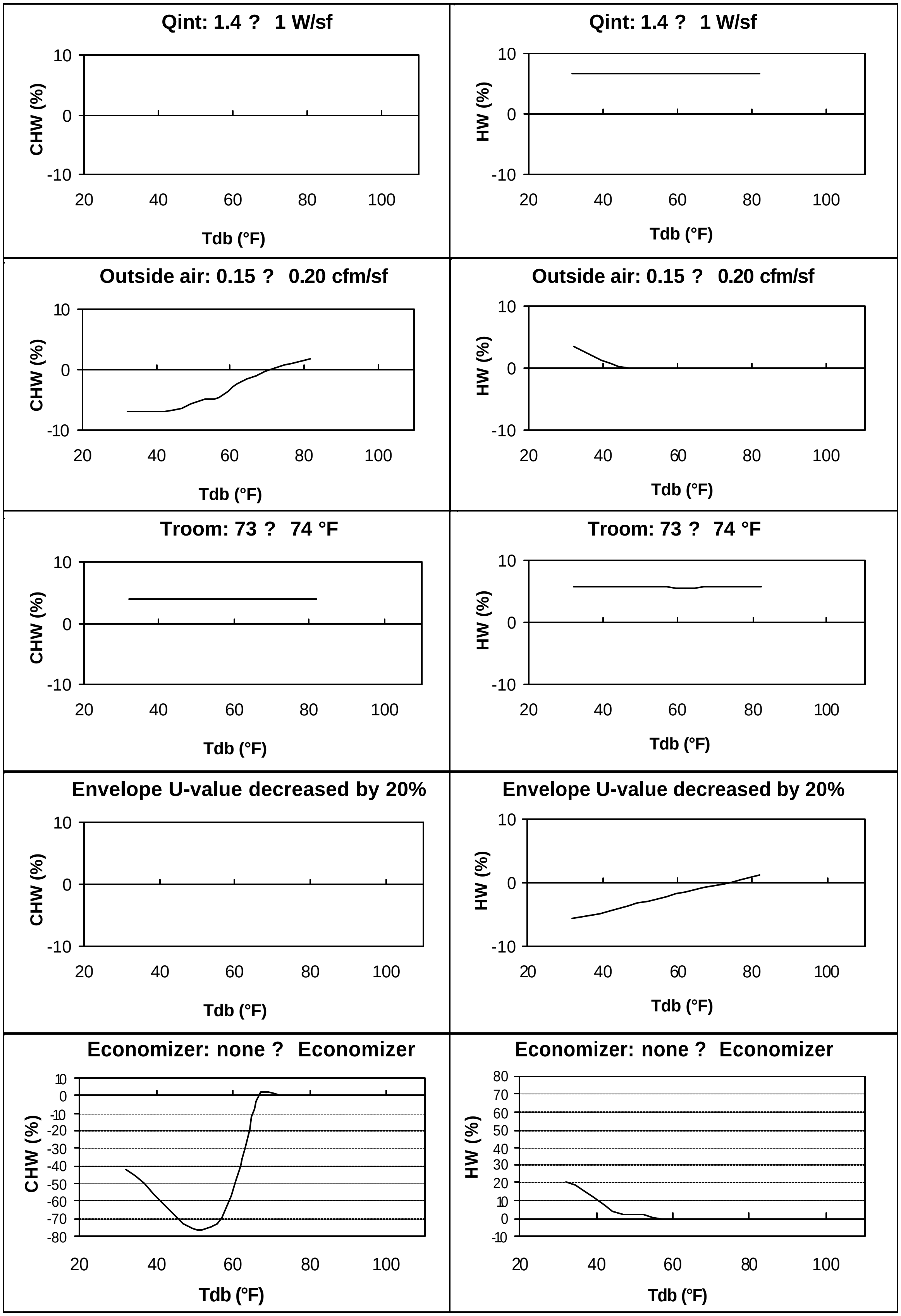






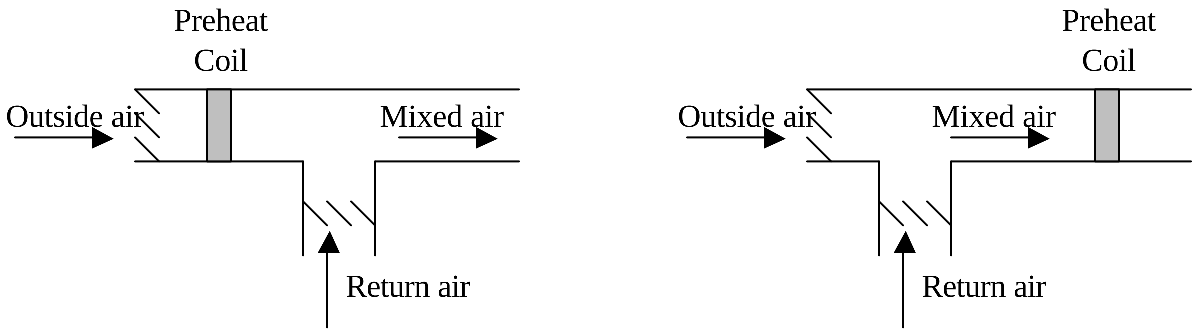





Qint: 1.4 ? 1 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 20%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 20%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

AIR HANDLING UNITS WITH PREHEATING AFTER MIXING

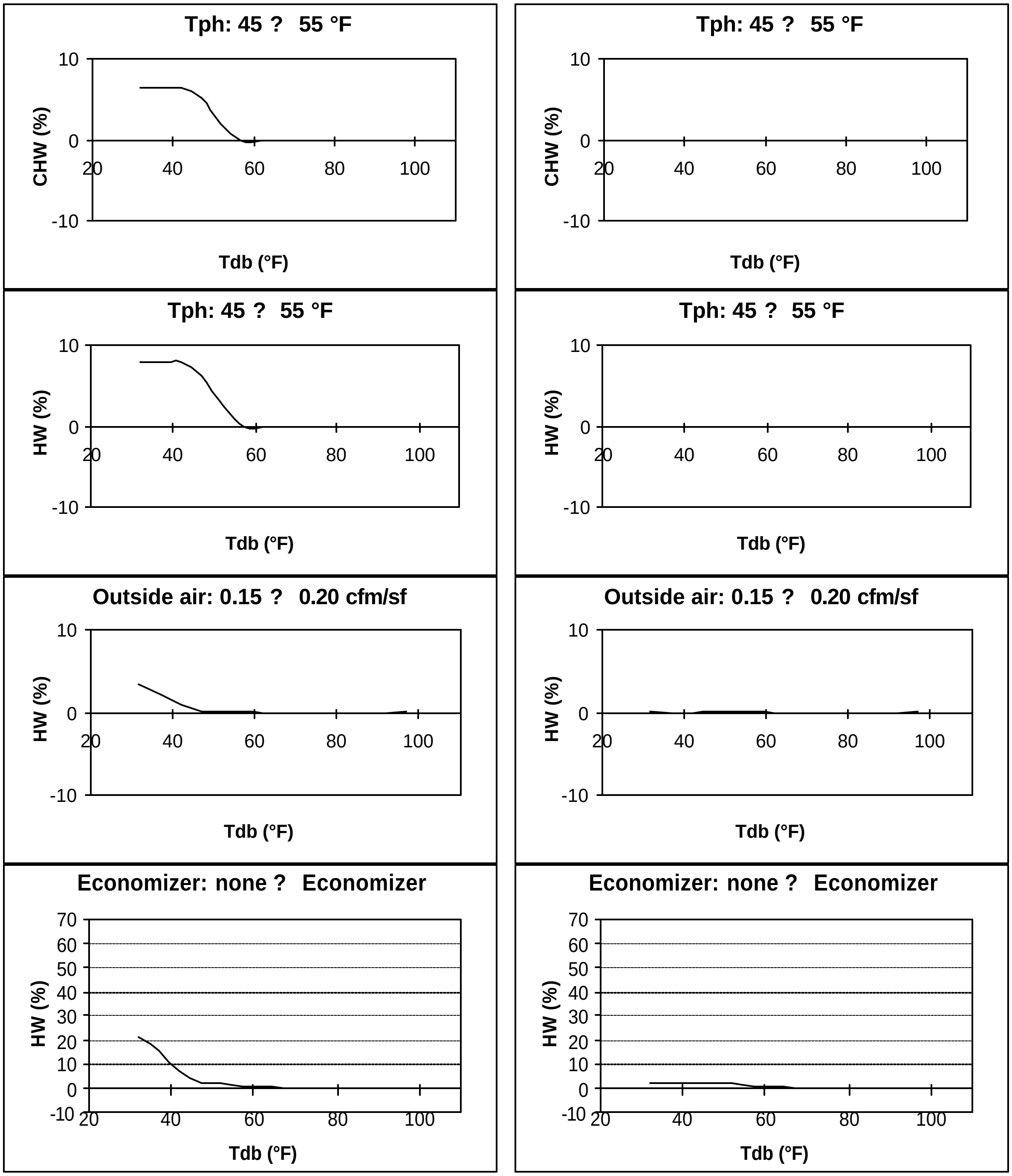
As shown in Figure C-1, the preheat coil can be located in the outside air or the mixed air stream.



a) Preheat located in outside air stream b) Preheat located in mixed air stream

Figure C-1. Preheat Locations

Systems used to generate characteristic signatures in this manual have preheating in the outside air stream as shown in Figure C-1a. However, the sets of characteristic signatures provided in this Appendix can be used for systems with preheat in either location. The main differences occur at the lower range of outside air temperatures where the preheating temperature setpoint can be higher than the outside air temperature but lower than the mixed air temperature. Figure C-2 shows the characteristic signatures that differ between a Single Duct Constant Volume system with preheat at the outside air stream and the same system type with preheat at the mixed air stream for Pasadena weather. The other characteristic signatures are similar.



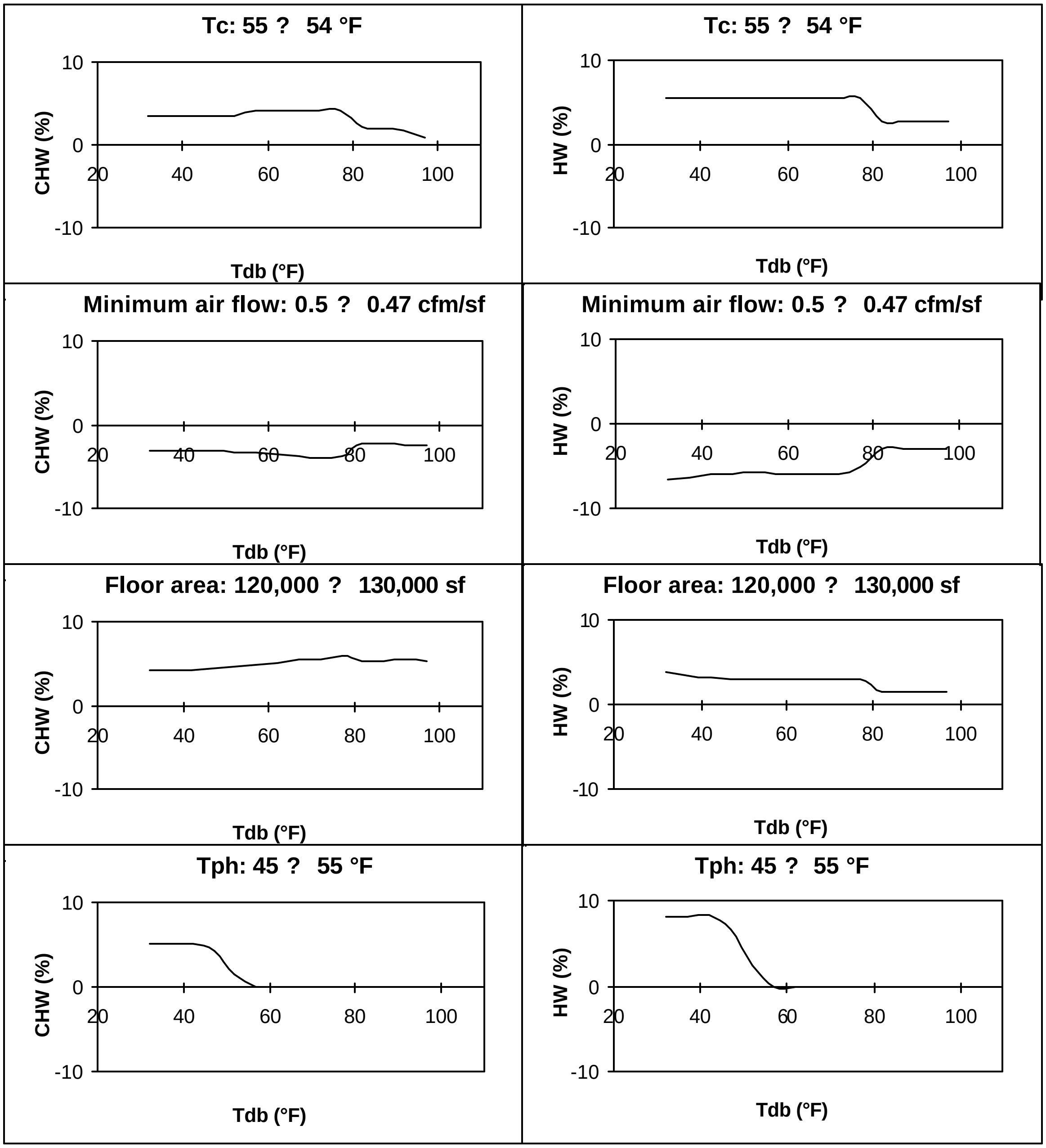
a) SDCV system with preheat at outside air stream

b) SDCV system with preheat at mixed air stream

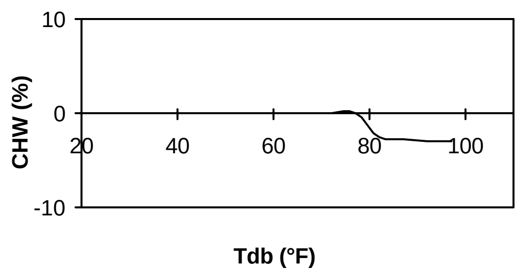
Figure C-2. Comparison of calibration signatures for different preheat locations

APPENDIX D: CHARACTERISTIC SIGNATURES FOR SDVAV SYSTEMS

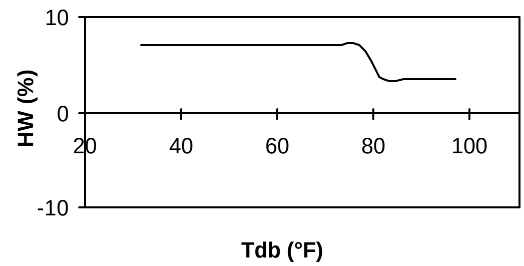
APPENDIX D-1: SDVAV SYSTEM IN PASADENA



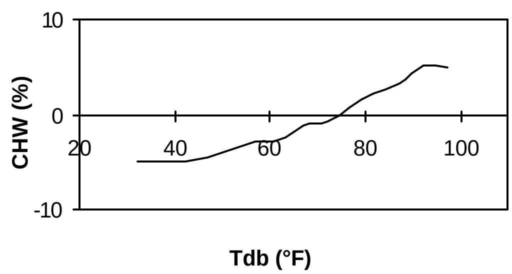
Qint: 1.4 ? 1.2 W/sf



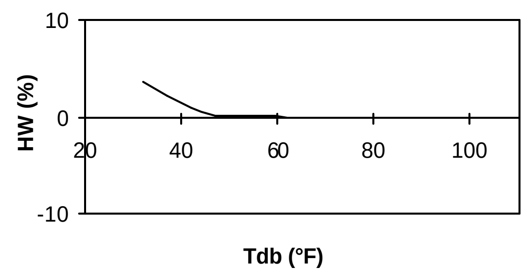
Qint: 1.4 ? 1.2 W/sf



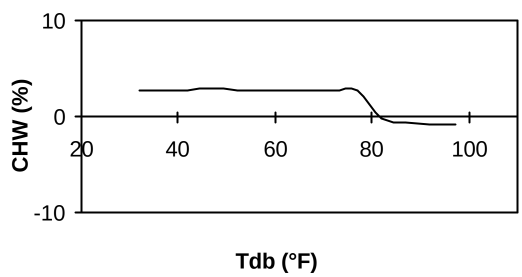
Outside air: 0.15 ? 0.20 cfm/sf



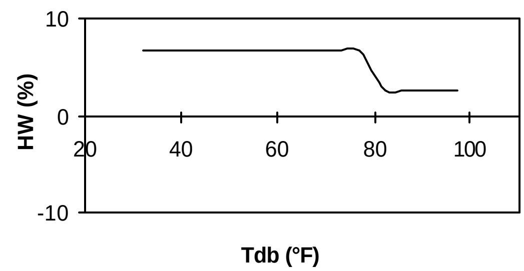
Outside air: 0.15 ? 0.20 cfm/sf



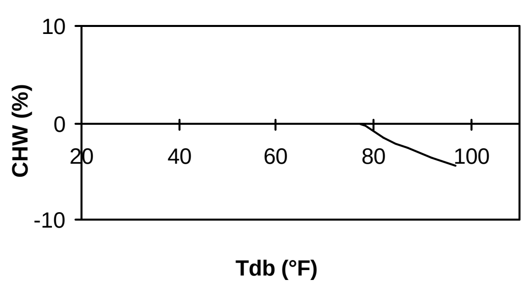
Troom: 73 ? 74 °F



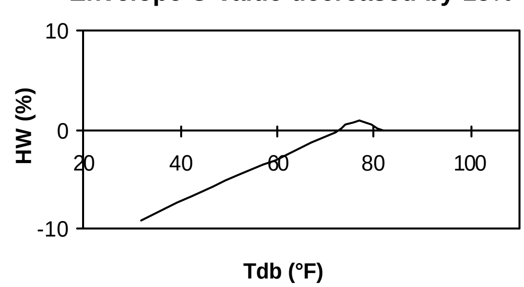
Troom: 73 ? 74 °F



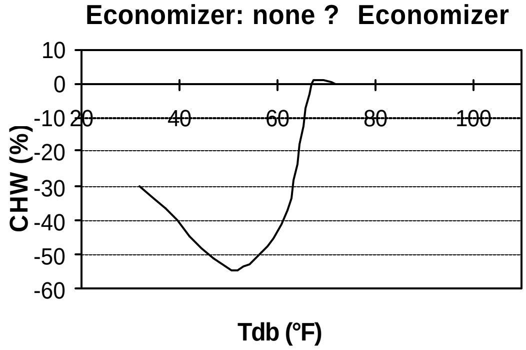
Envelope U-value decreased by 15%



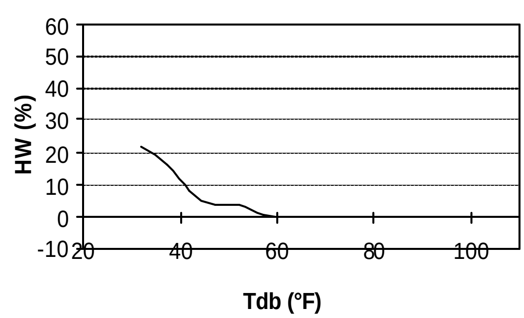
Envelope U-value decreased by 15%



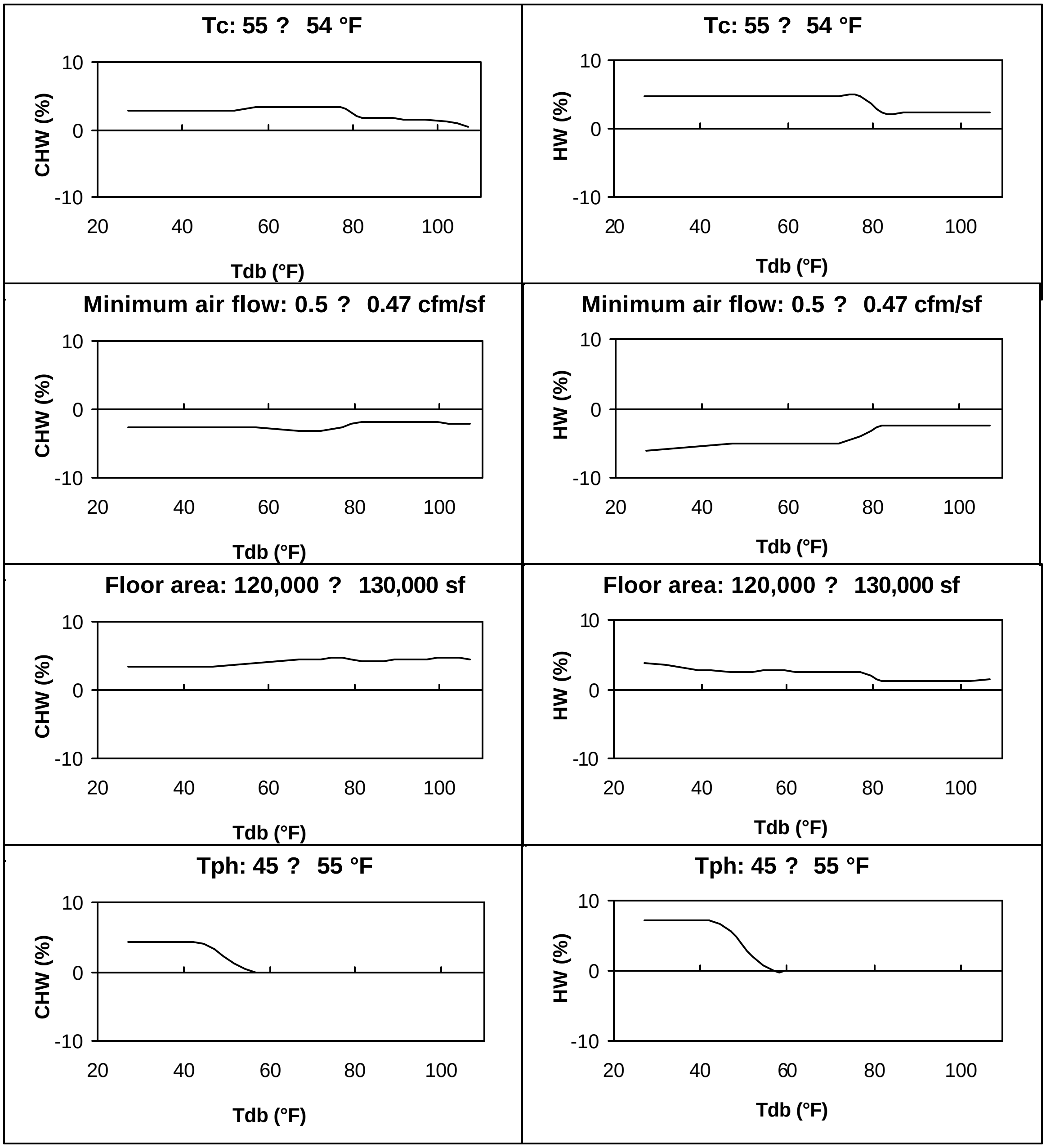
Economizer: none ? Economizer



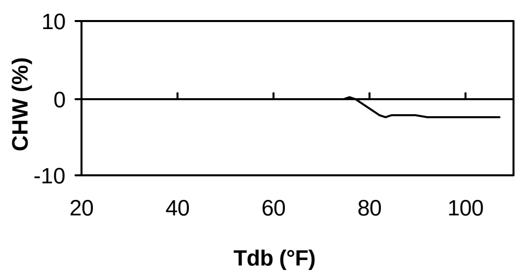
Economizer: none ? Economizer



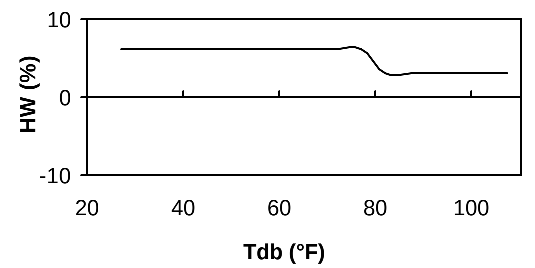
APPENDIX D-2: SDVAV SYSTEM IN SACRAMENTO



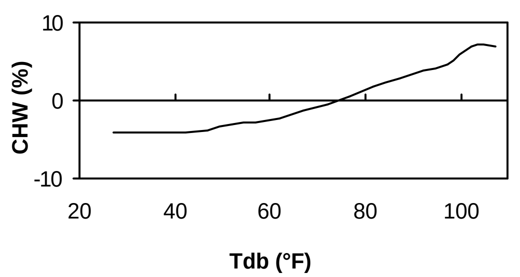
Qint: 1.4 ? 1.2 W/sf



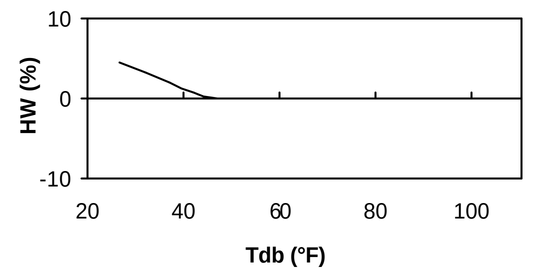
Qint: 1.4 ? 1.2 W/sf



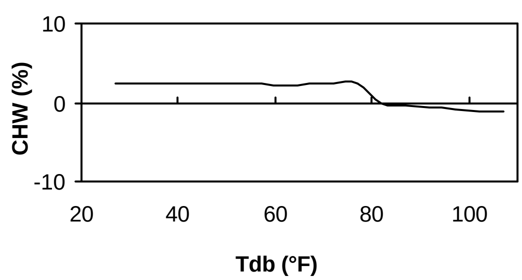
Outside air: 0.15 ? 0.20 cfm/sf



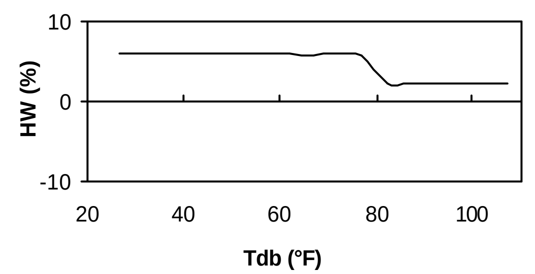
Outside air: 0.15 ? 0.20 cfm/sf



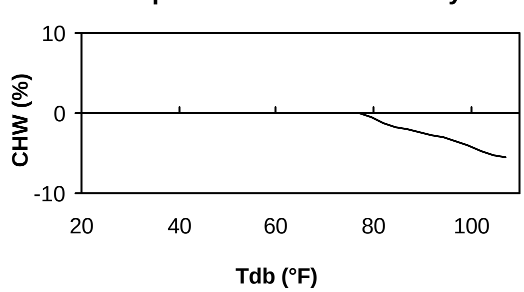
Troom: 73 ? 74 °F



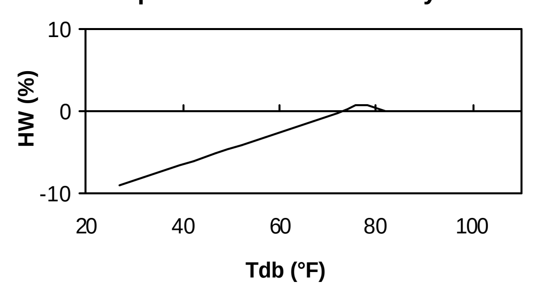
Troom: 73 ? 74 °F



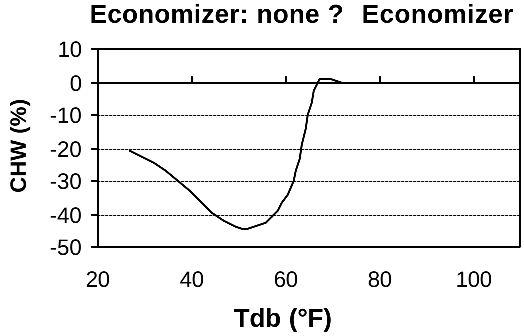
Envelope U-value decreased by 15%



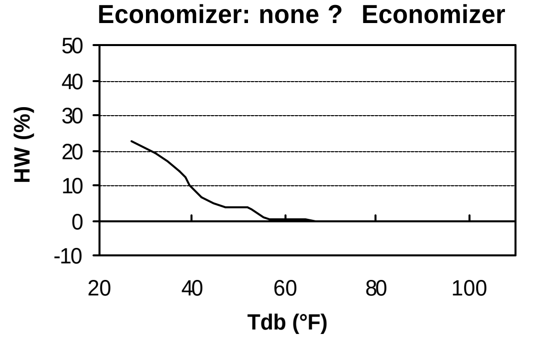
Envelope U-value decreased by 15%



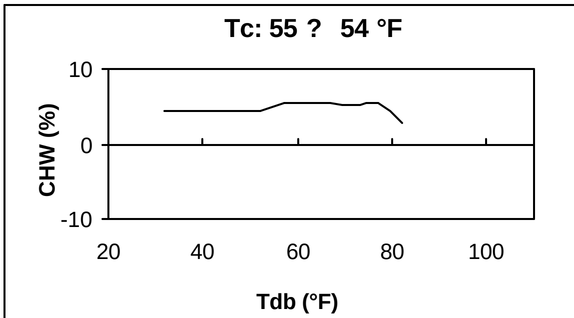
Economizer: none ? Economizer

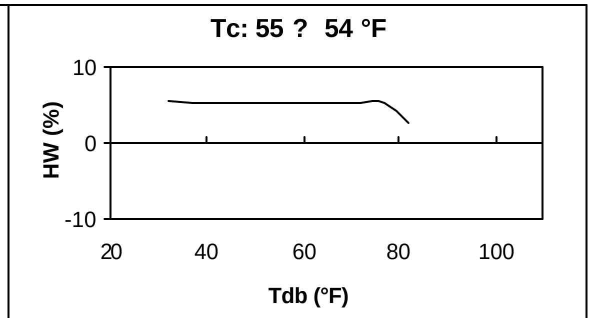


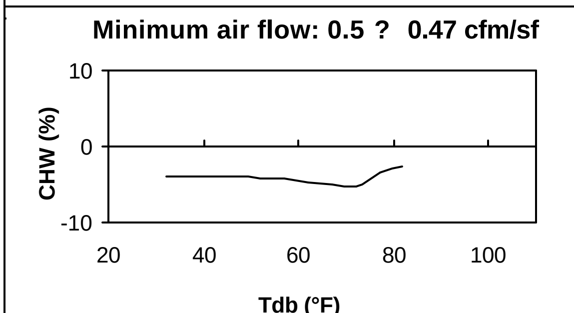
Economizer: none ? Economizer

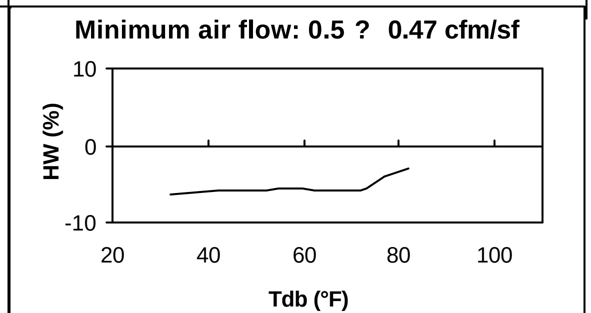


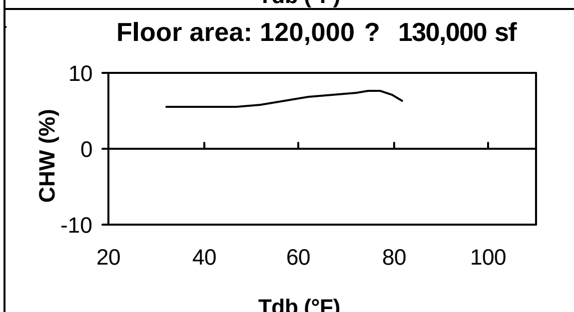
APPENDIX D-3: SDVAV SYSTEM IN OAKLAND

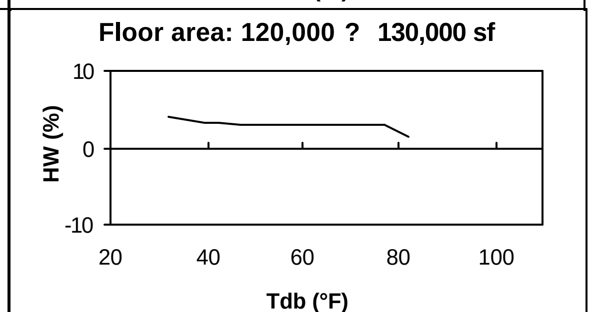


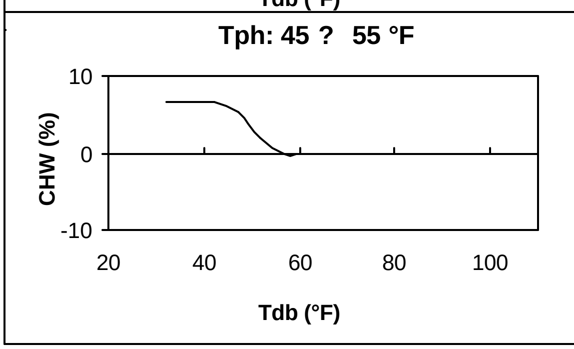


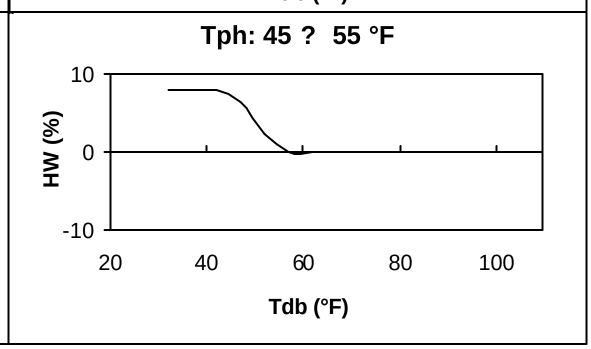


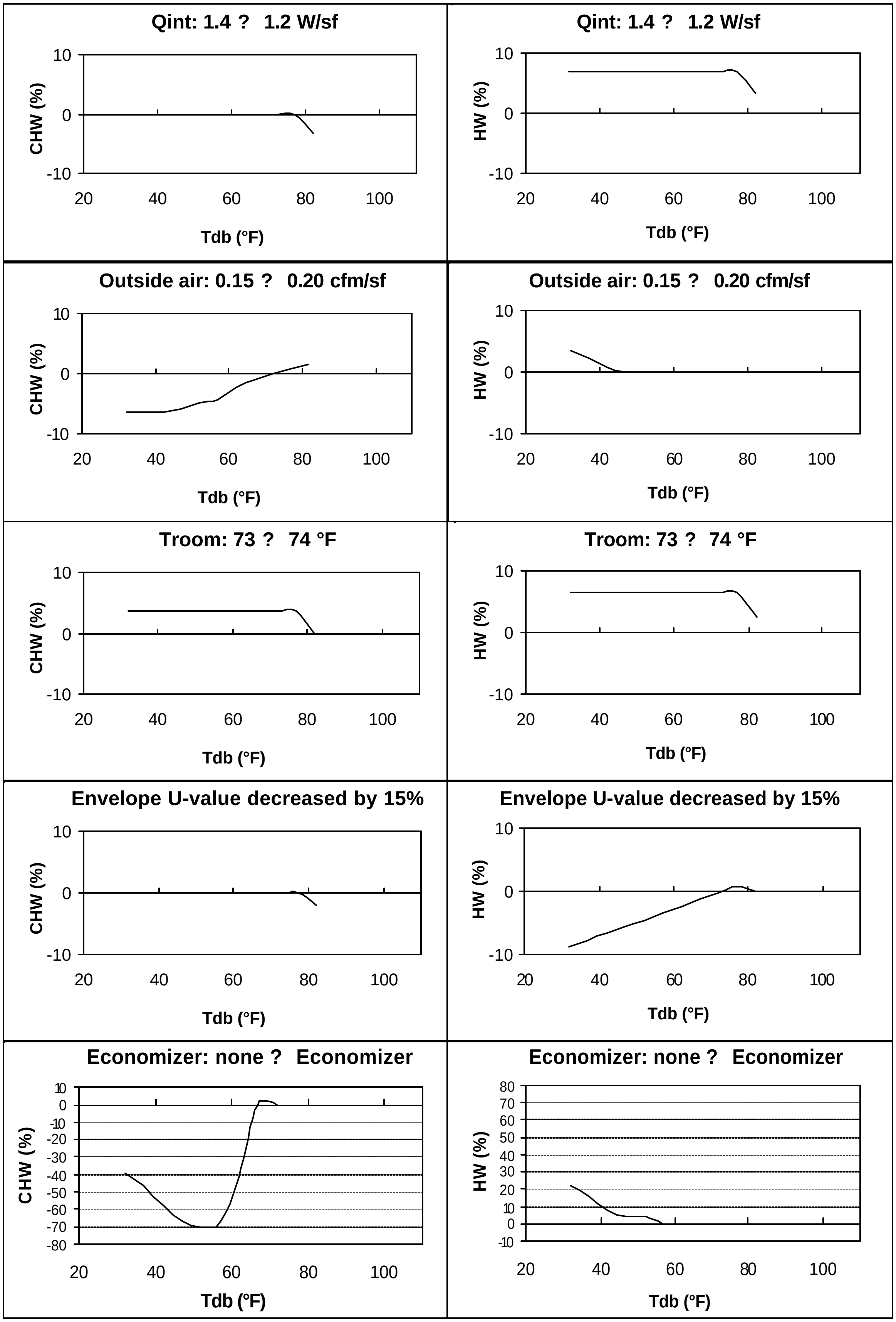








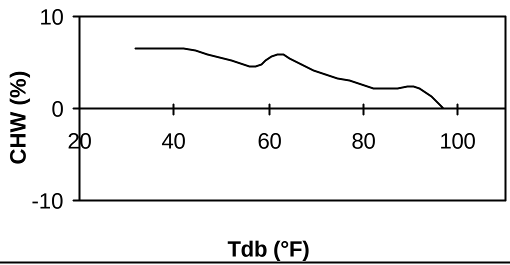



Qint: 1.4 ? 1.2 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1.2 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 15%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 15%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

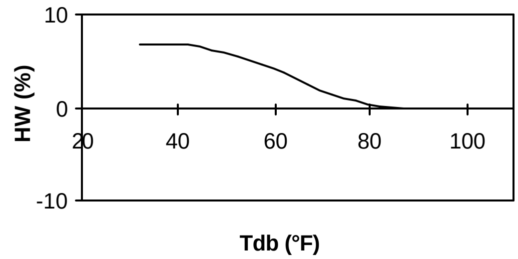
APPENDIX E: CHARACTERISTIC SIGNATURES FOR DDCV SYSTEMS

APPENDIX E-1: DDCV SYSTEM IN PASADENA

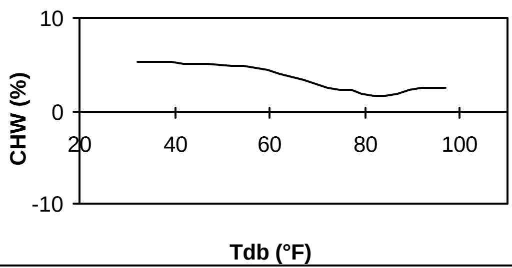
Tc: 55 ? 53 °F



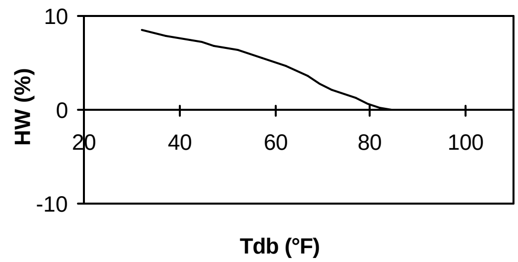
Tc: 55 ? 53 °F



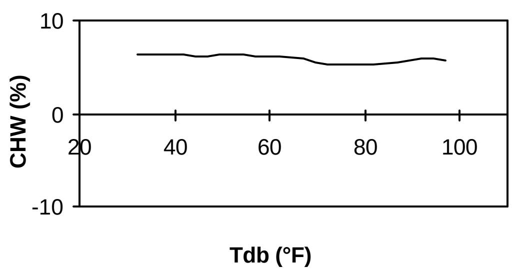
Supply air: 1 ? 1.08 cfm/sf



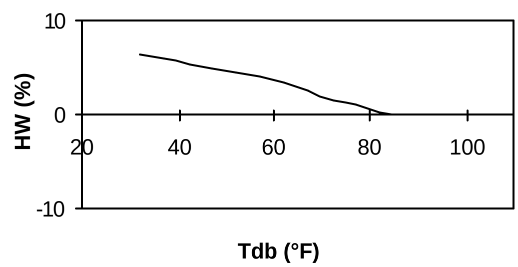
Supply air: 1 ? 1.08 cfm/sf



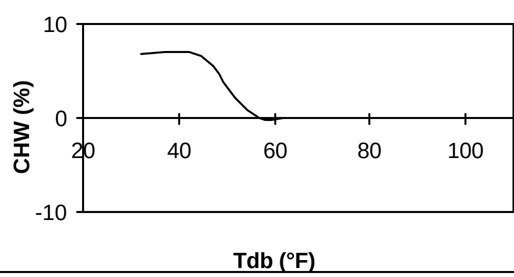
Floor area: 120,000 ? 130,000 sf



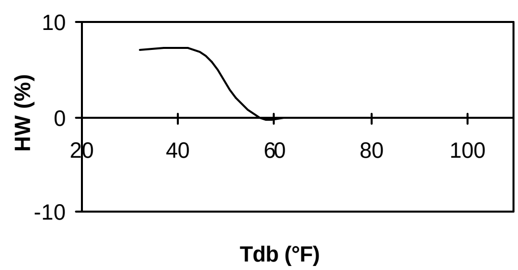
Floor area: 120,000 ? 130,000 sf



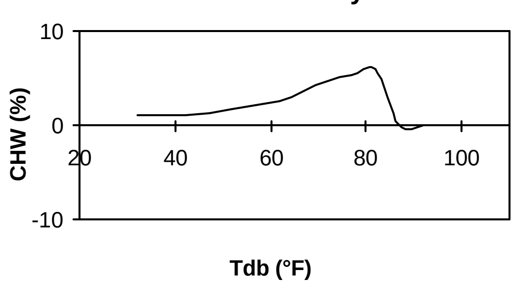
Tph: 45 ? 55 °F



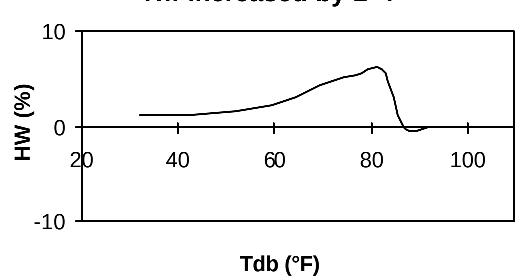
Tph: 45 ? 55 °F



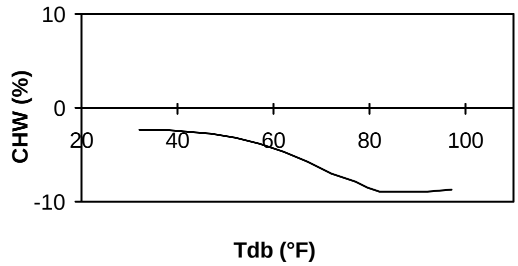
Th: increased by 2 °F



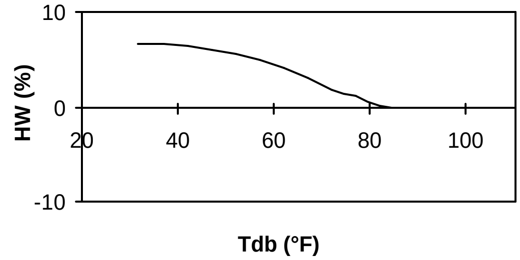
Th: increased by 2 °F



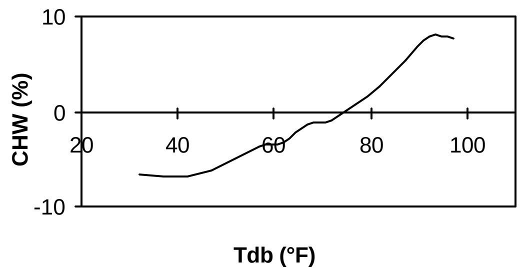
Qint: 1.4 ? 1 W/sf



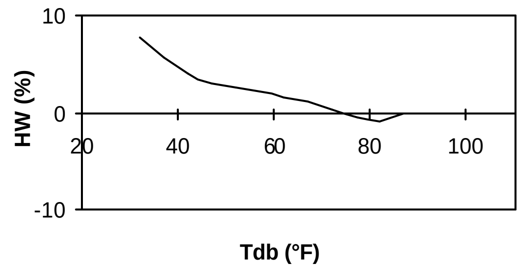
Qint: 1.4 ? 1 W/sf



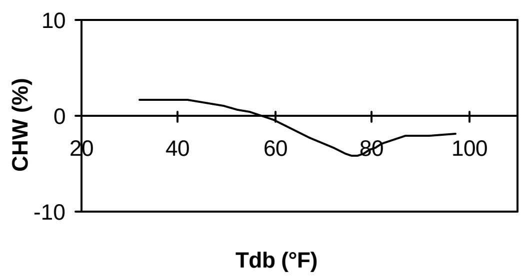
Outside air: 0.15 ? 0.20 cfm/sf



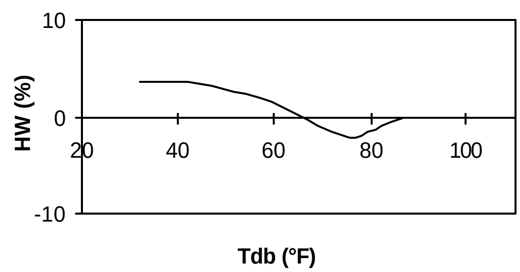
Outside air: 0.15 ? 0.20 cfm/sf



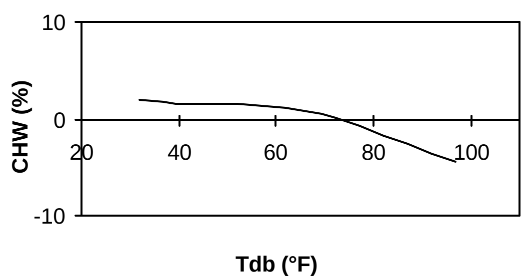
Troom: 73 ? 74 °F



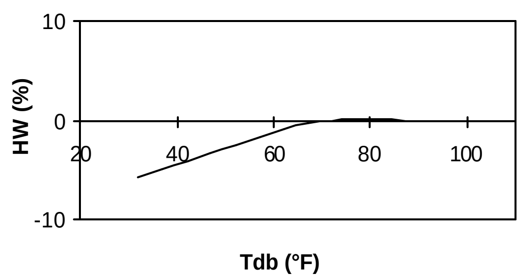
Troom: 73 ? 74 °F



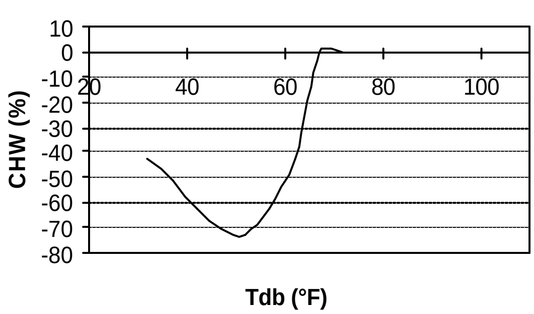
Envelope U-value decreased by 20%



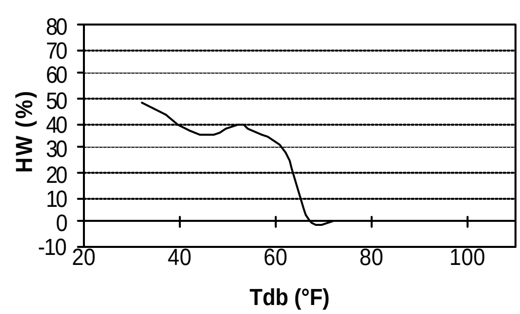
Envelope U-value decreased by 20%



Economizer: none ? Economizer

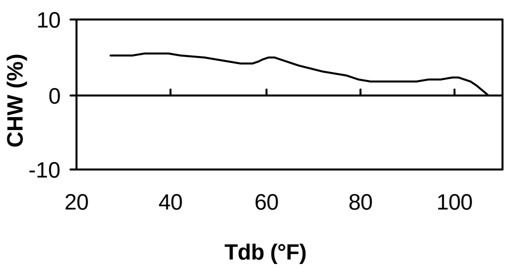


Economizer: none ? Economizer

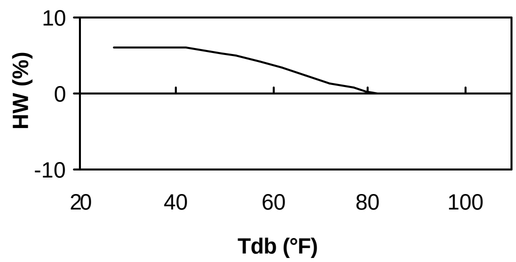


APPENDIX E-2: DDCV SYSTEM IN SACRAMENTO

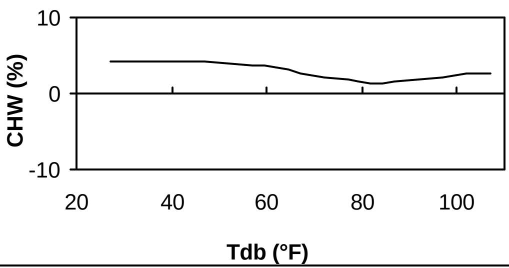
Tc: 55 ? 53 °F



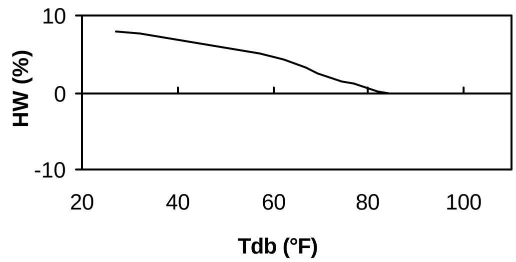
Tc: 55 ? 53 °F



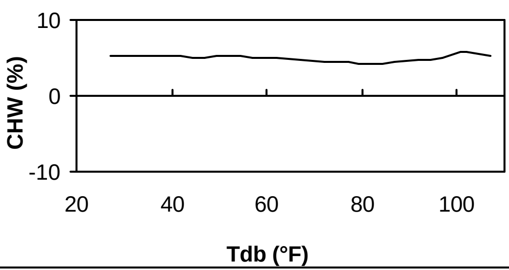
Supply air: 1.0 ? 1.08 cfm/sf



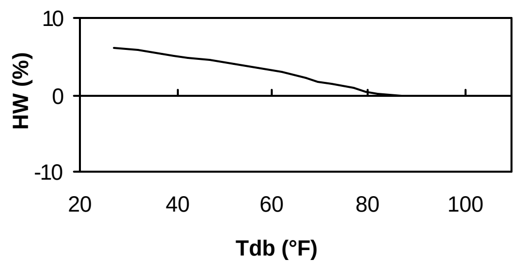
Supply air: 1.0 ? 1.08 cfm/sf



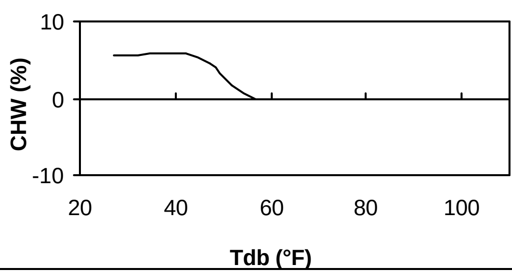
Floor area: 120,000 ? 130,000 sf



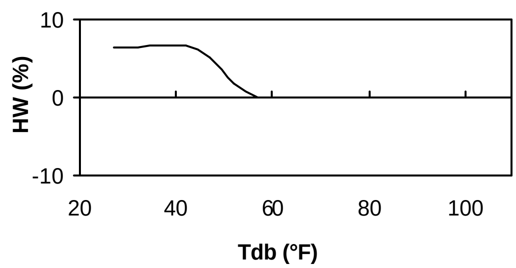
Floor area: 120,000 ? 130,000 sf



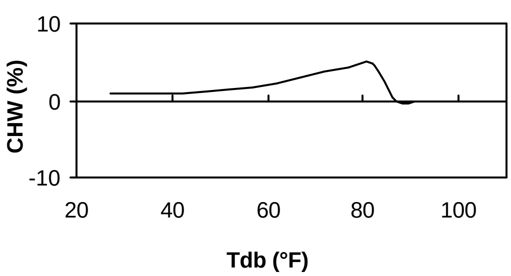
Tph: 45 ? 55 °F



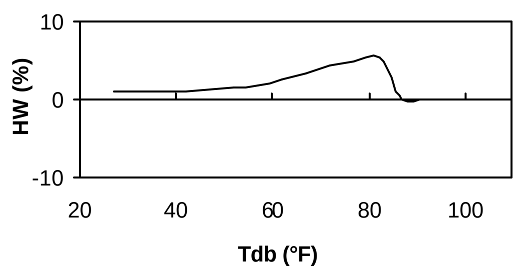
Tph: 45 ? 55 °F



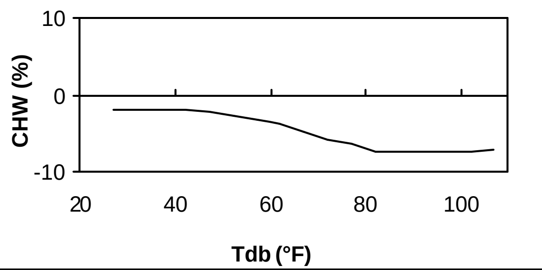
Th: increased by 2 °F



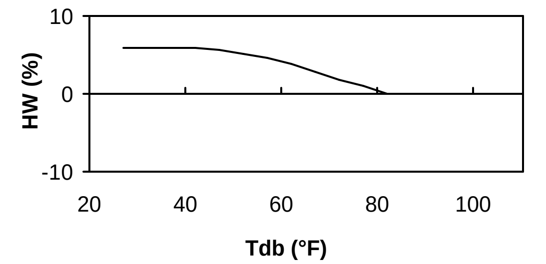
Th: increased by 2 °F



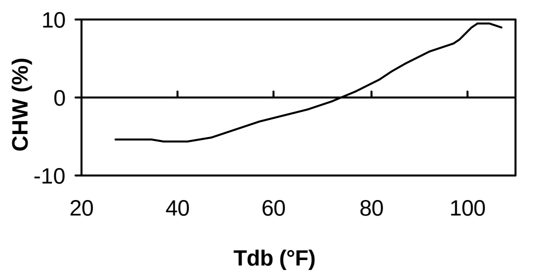
Qint: 1.4 ? 1 W/sf



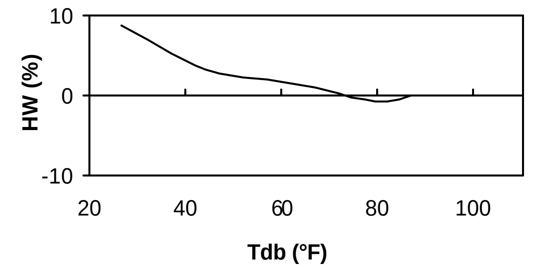
Qint: 1.4 ? 1 W/sf



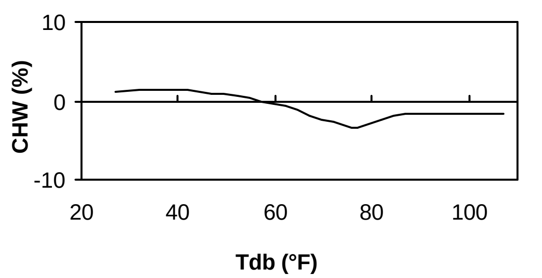
Outside air: 0.15 ? 0.20 cfm/sf



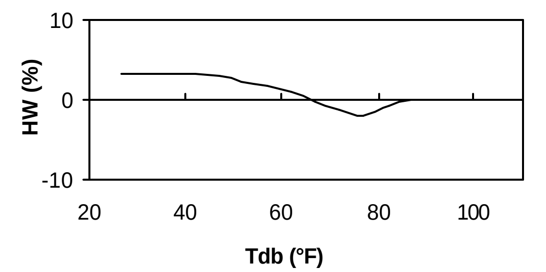
Outside air: 0.15 ? 0.20 cfm/sf



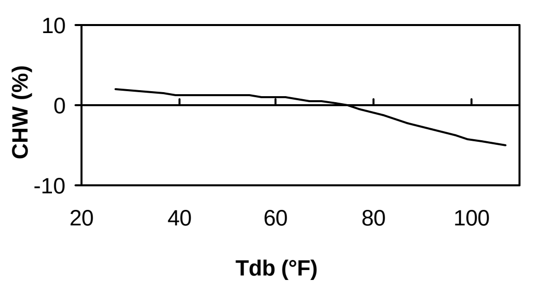
Troom: 73 ? 74 °F



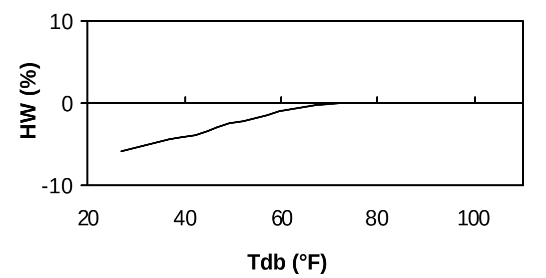
Troom: 73 ? 74 °F



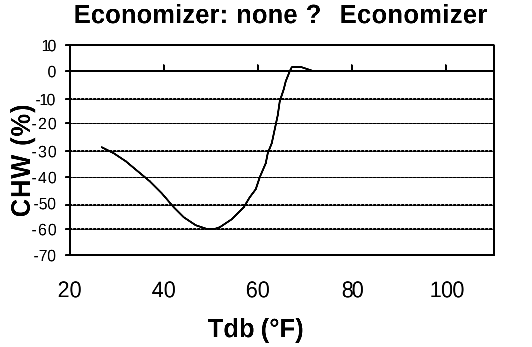
Envelope U-value decreased by 20%



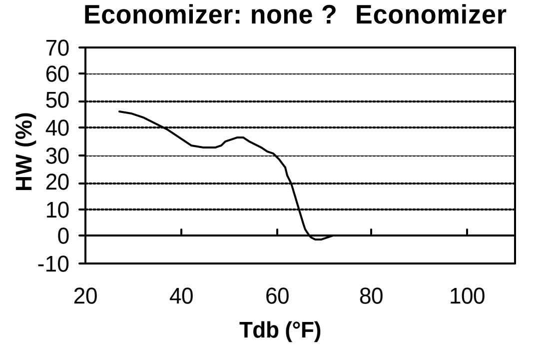
Envelope U-value decreased by 20%



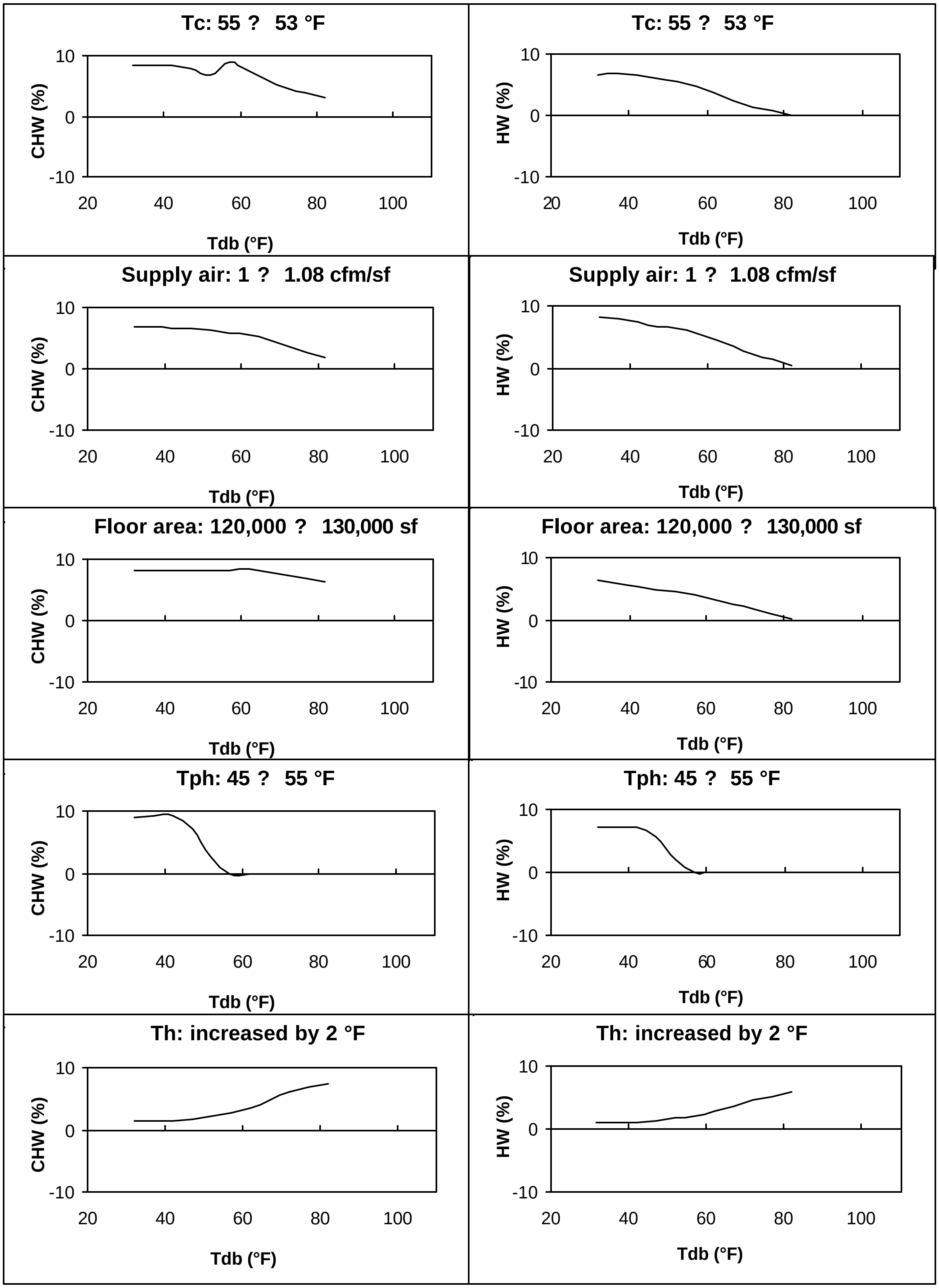
Economizer: none ? Economizer



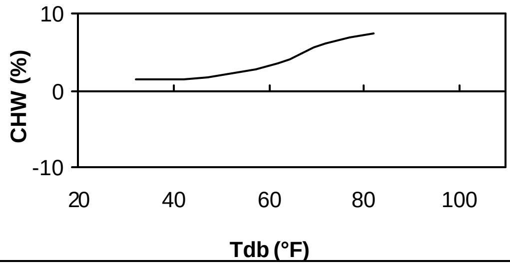
Economizer: none ? Economizer



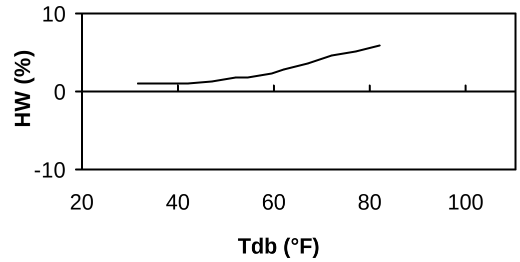
APPENDIX E-3: DDCV SYSTEM IN OAKLAND



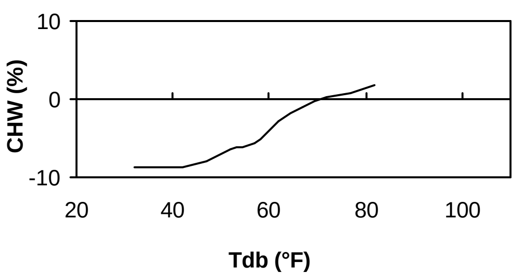
Qint: 1.4 ? 1 W/sf



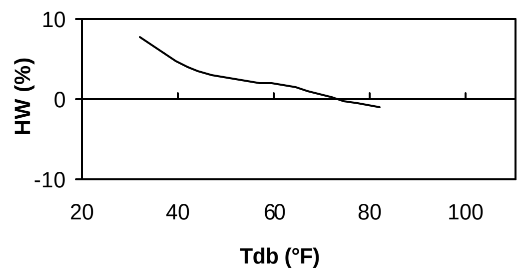
Qint: 1.4 ? 1 W/sf



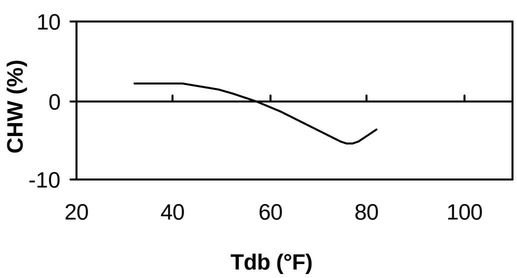
Outside air: 0.15 ? 0.20 cfm/sf



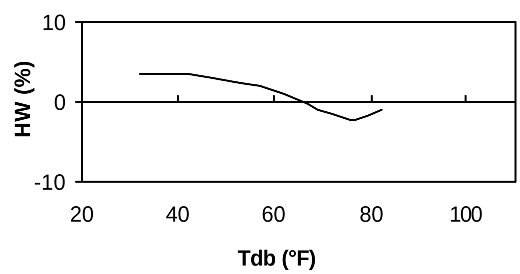
Outside air: 0.15 ? 0.20 cfm/sf



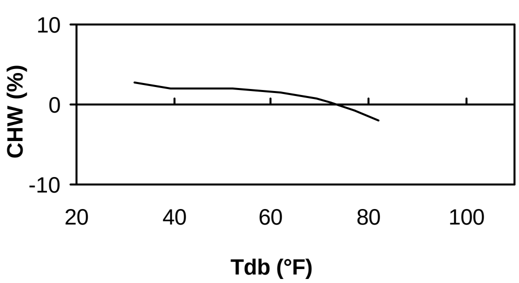
Troom: 73 ? 74 °F



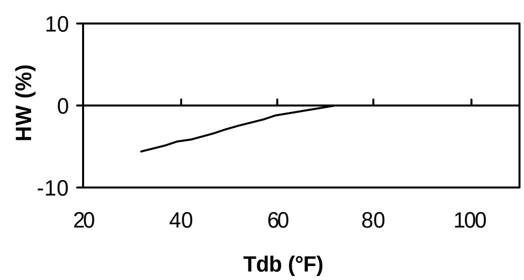
Troom: 73 ? 74 °F



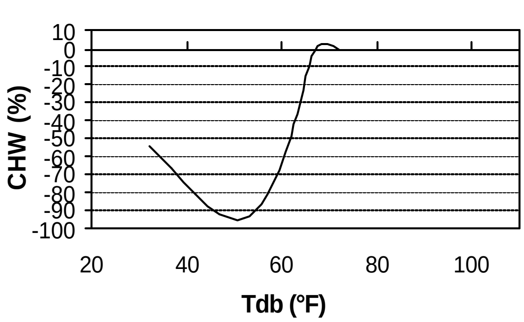
Envelope U-value decreased by 20%



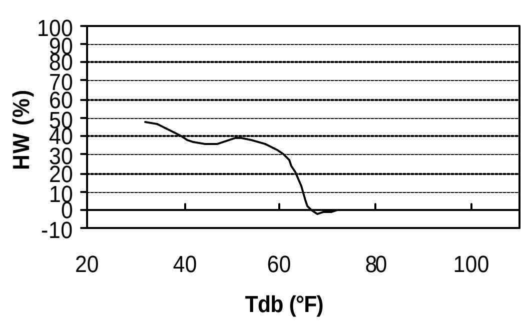
Envelope U-value decreased by 20%



Economizer: none ? Economizer

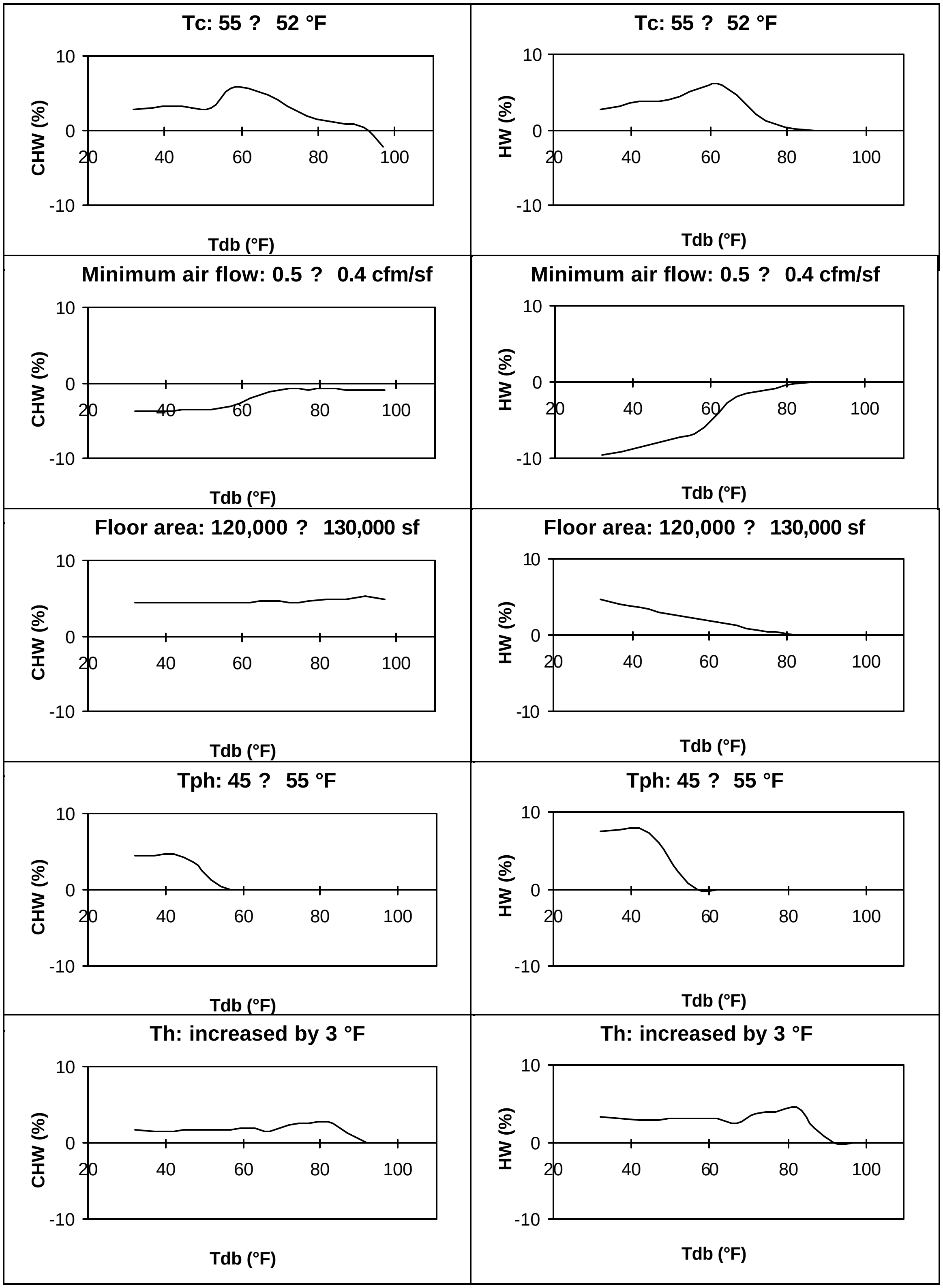


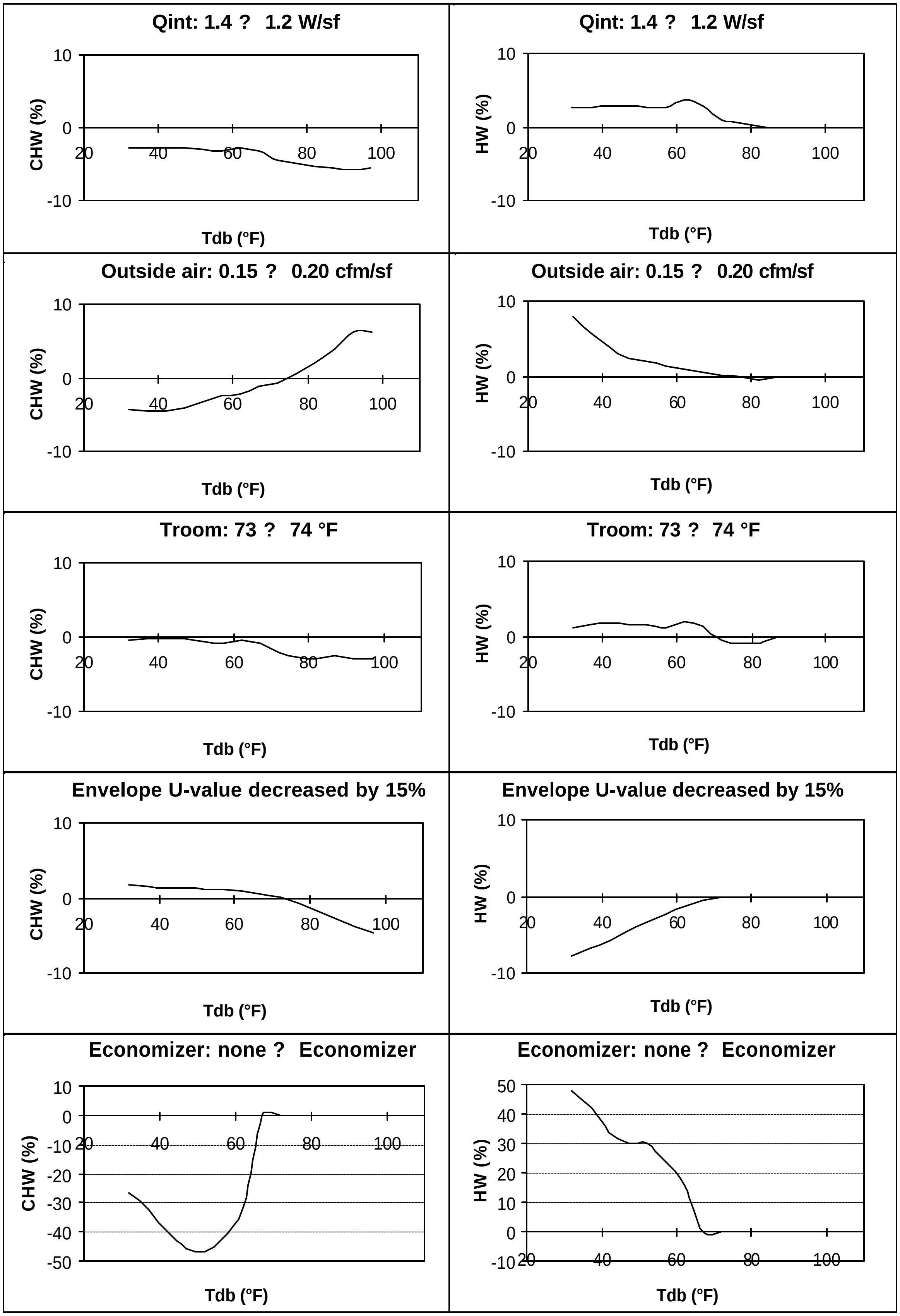
Economizer: none ? Economizer



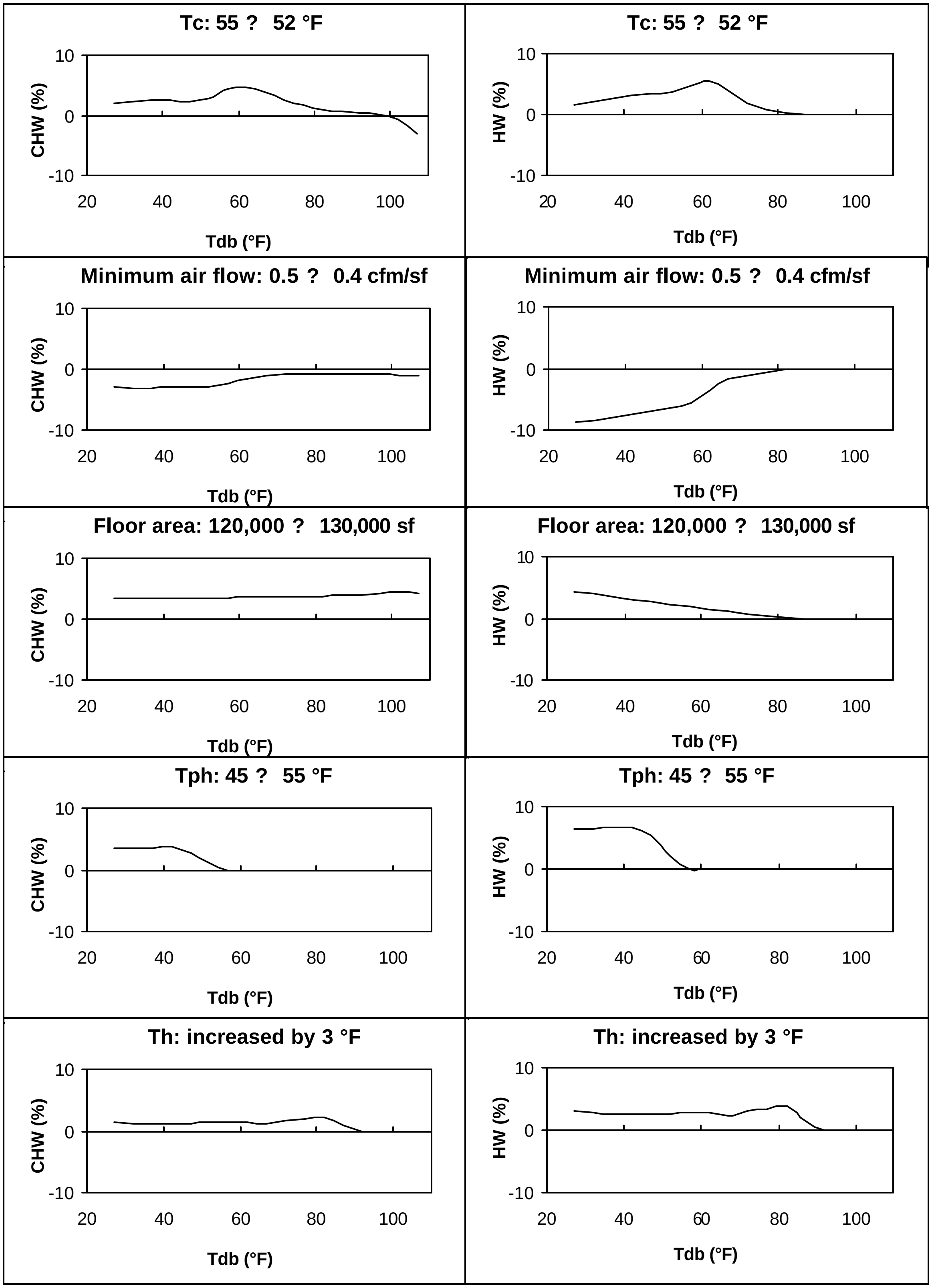
APPENDIX F: CHARACTERISTIC SIGNATURES FOR DDVAV SYSTEMS

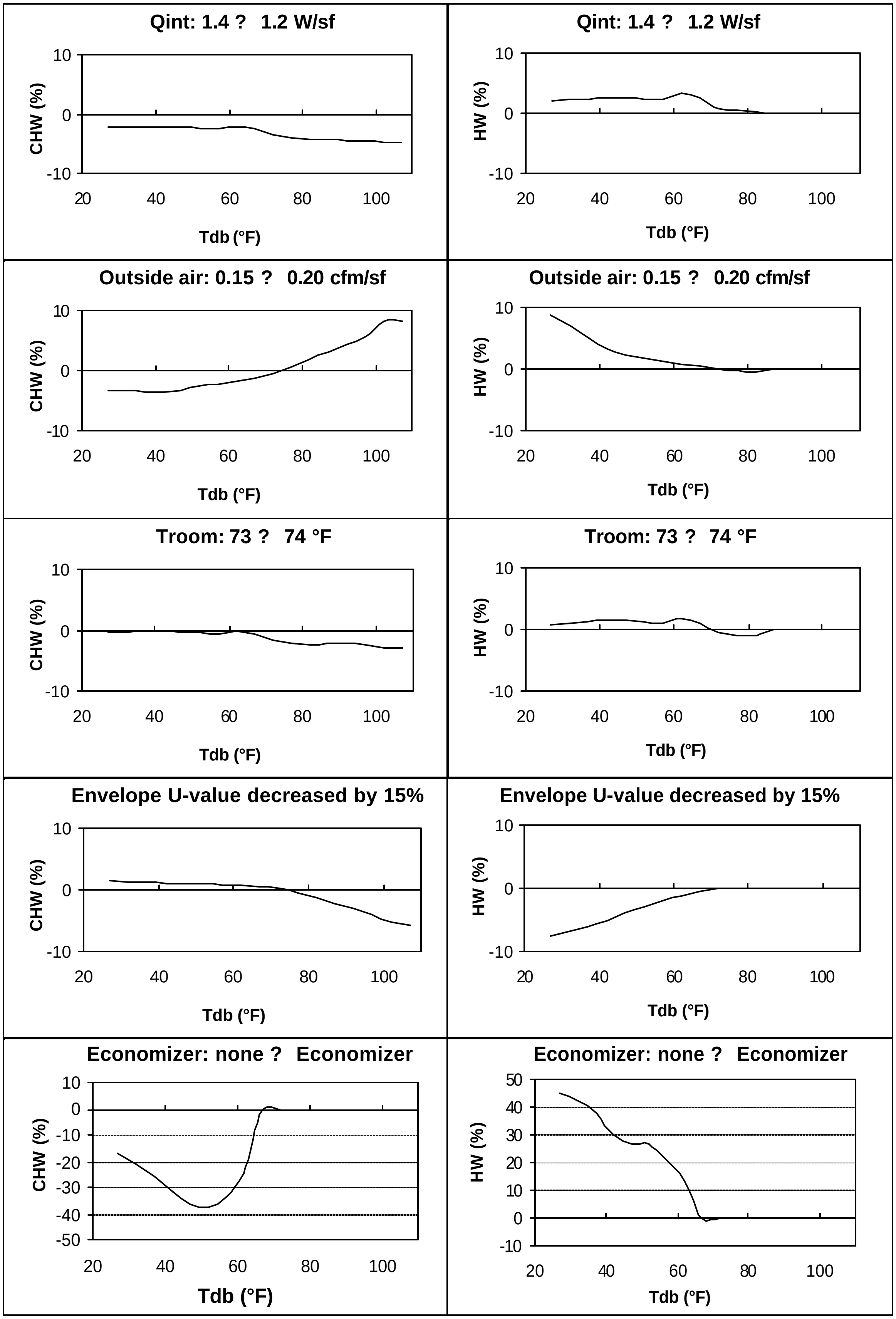
APPENDIX F-1: DDVAV SYSTEM IN PASADENA



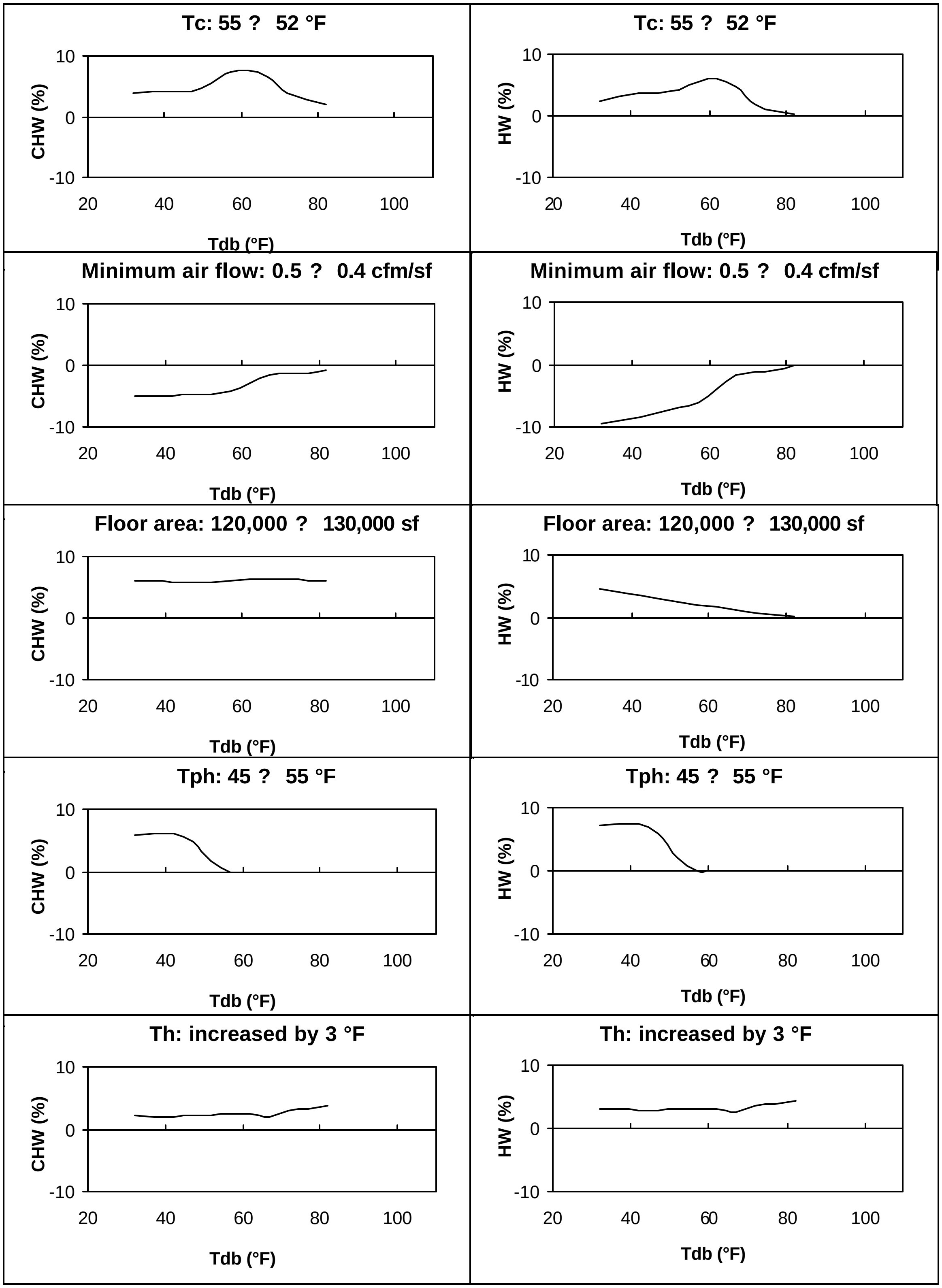

Qint: 1.4 ? 1.2 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1.2 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 15%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 15%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

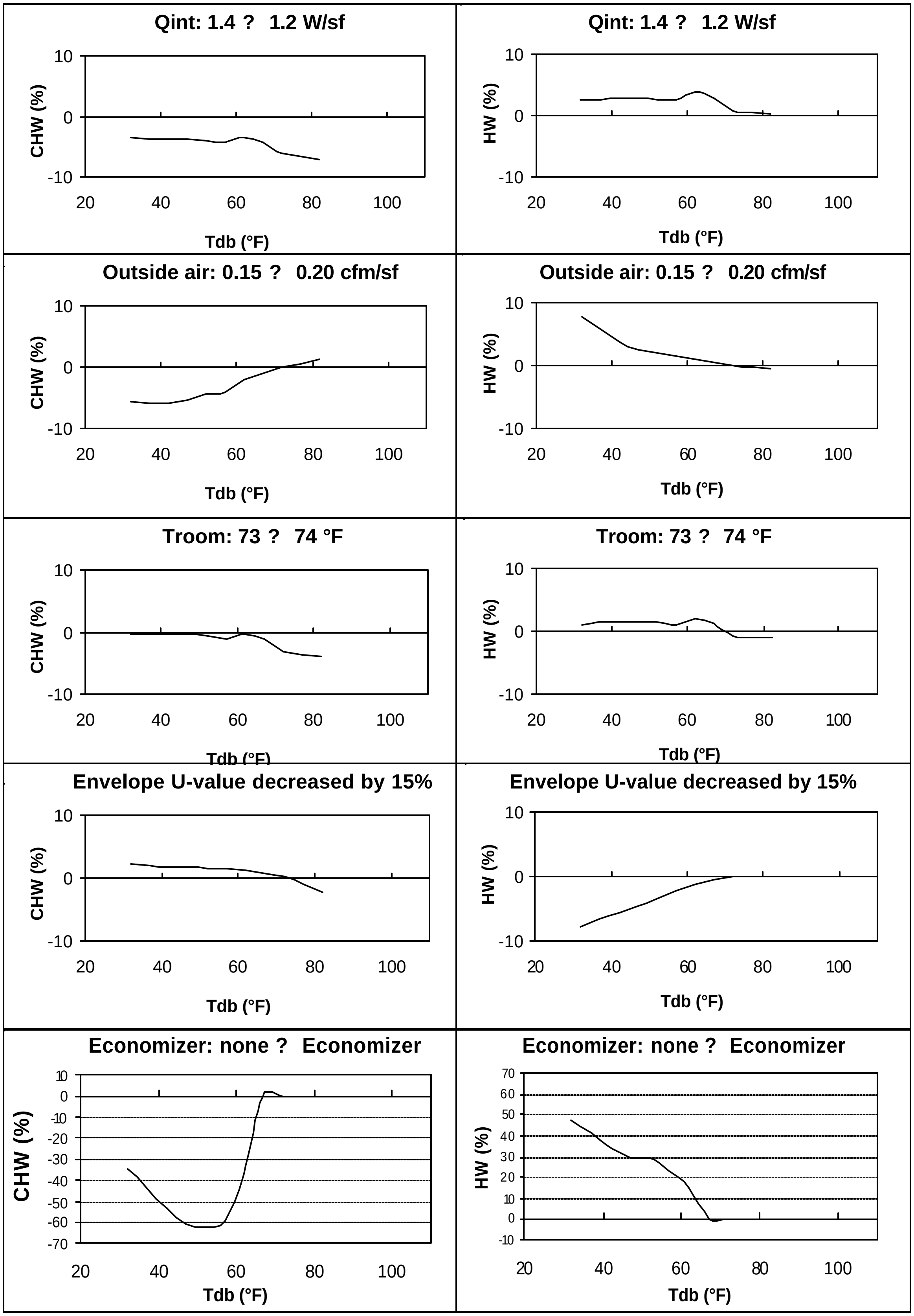
APPENDIX F-2: DDVAV SYSTEM IN SACRAMENTO




Qint: 1.4 ? 1.2 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ? 1.2 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ? 0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ? 74 °F
CHW (%)
Tdb (°F)
Troom: 73 ? 74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 15%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 15%
HW (%)
Tdb (°F)
Economizer: none ? Economizer
CHW (%)
Tdb (°F)
Economizer: none ? Economizer
HW (%)
Tdb (°F)

APPENDIX F-3: DDVAV SYSTEM IN OAKLAND




Qint: 1.4 ?   1.2 W/sf
CHW (%)
Tdb (°F)
Qint: 1.4 ?   1.2 W/sf
HW (%)
Tdb (°F)
Outside air: 0.15 ?   0.20 cfm/sf
CHW (%)
Tdb (°F)
Outside air: 0.15 ?   0.20 cfm/sf
HW (%)
Tdb (°F)
Troom: 73 ?   74 °F
CHW (%)
Tdb (°F)
Troom: 73 ?   74 °F
HW (%)
Tdb (°F)
Envelope U-value decreased by 15%
CHW (%)
Tdb (°F)
Envelope U-value decreased by 15%
HW (%)
Tdb (°F)
Economizer: none ?   Economizer
CHW (%)
Tdb (°F)
Economizer: none ?   Economizer
HW (%)
Tdb (°F)

APPENDIX G: CREATING YOUR OWN CHARACTERISTIC SIGNATURES

Sets of calibration signatures have been provided in this manual for the four major air handling unit types for three California weather conditions. There may be a need to create one's own calibration signatures for other weather conditions or other variations of air handling unit types, or to test the sensitivity of other input parameters not tested in the provided sets.

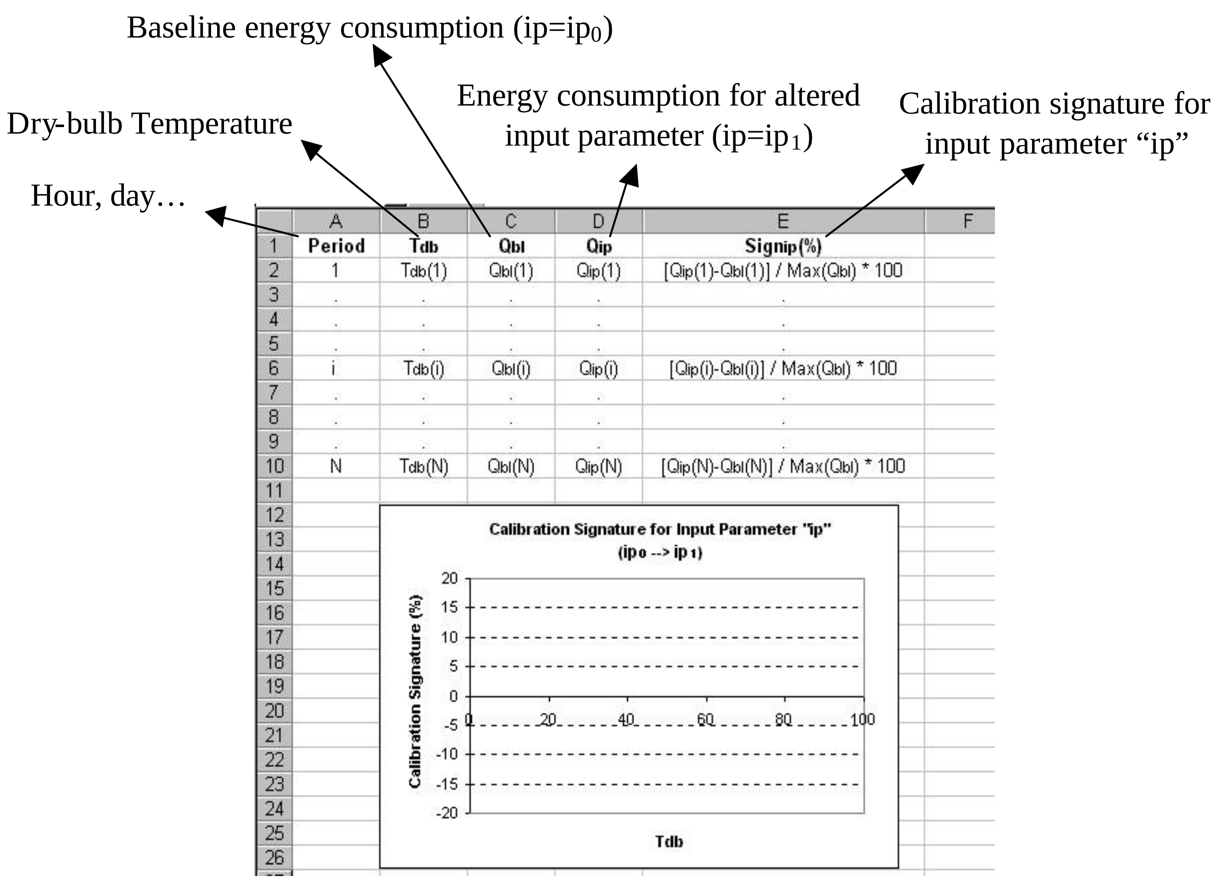
It is preferable to use the initial simulation, which is based on the best approximation of input parameters, as the baseline for calibration signatures. Figure G-1 illustrates how a calibration signature is created for an input parameter "ip" using a spreadsheet. MS Excel was used for this purpose.

Any simulation program may be used. Simulated data is then copied and pasted in the spreadsheet to create the signature. In Figure G-1, dry-bulb Temperatures were pasted in column B for the corresponding time steps in column A. Weather data can be hourly, daily… or bin data. The baseline simulation data was pasted in column C with the caption Q_{bl}. It could be either cooling or heating energy consumption. In this initial simulation, the input parameter "ip" had an initial value ip_0. To create the calibration signature for this parameter, its value was altered in the input file from ip_0 to ip_1 and the simulation was rerun. Simulated data was then pasted in column D with the caption Q_p and the calibration signature was calculated in column E for line "i" as:

$$\textit{Calibration Signature for input parameter "ip"} = \frac{Q_{ip}(i) - Q_{bl}(i)}{Max\ (Q_{bl})} \quad x\ 100\% \qquad \text{(G-1)}$$

Max (Q_{bl}) is the maximum baseline simulated value for the whole simulation period. Note that it would be different for cooling and heating. The input parameter is changed to an amount that gives a significant change in energy consumption, typically up to 10%.

Figure G-2 shows the calculation of the cooling calibration signature of the supply air flow rate for a SDCV system. This simulation uses bin data. The baseline simulation was run with a supply air flow rate of 1 cfm/ft^2 and the second simulation was run with a value of 1.08 cfm/ft^2. Signature points were connected with a smoothed line to show the impact of the input parameter over the entire range of dry-bulb Temperatures.



	A	B	C	D	E
1	Period	Tdb	Qbl	Qip	Signip(%)
2	1	Tdb(1)	Qbl(1)	Qip(1)	[Qip(1)-Qbl(1)] / Max(Qbl) * 100
3	.	.	.	.	.
4	.	.	.	.	.
5	.	.	.	.	.
6	i	Tdb(i)	Qbl(i)	Qip(i)	[Qip(i)-Qbl(i)] / Max(Qbl) * 100
7	.	.	.	.	.
8	.	.	.	.	.
9	.	.	.	.	.
10	N	Tdb(N)	Qbl(N)	Qip(N)	[Qip(N)-Qbl(N)] / Max(Qbl) * 100

Figure G-1. Creation of the Calibration Signature for Input Parameter "ip"

	A	B	C	D	E
1	Period	Tdb	Q-baseline	Q-supply air	Sign-supply air(%)
2		32	1.854	1.998	4.86
3		37	1.856	2	4.86
4		42	1.857	2.001	4.86
5		47	1.896	2.043	4.96
6		52	1.993	2.147	5.19
7		57	2.089	2.251	5.46
8		62	2.204	2.371	5.63
9		67	2.357	2.536	6.04
10		72	2.415	2.598	6.17
11		77	2.57	2.766	6.61
12		82	2.721	2.928	6.98
13		87	2.815	3.03	7.25
14		92	2.966	3.193	7.65
15		97	2.857	3.08	7.52

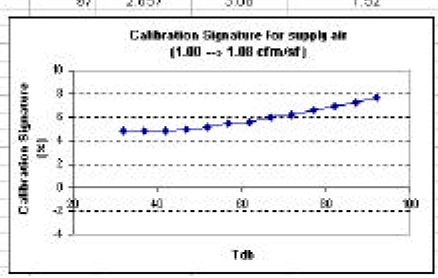


Figure G-2. Calibration Signature of Supply Air flow Rate for a SDCV System